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# OUTLINES

OF

# ASTRONOMY.

BY

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# PREFACE.

No one, probably, would maintain that a student who had no intention of attempting to read, speak, or write the Greek language, could spend his time profitably in committing a Greek grammar to memory; yet methods analogous to this are still sometimes employed in the study of science. No practical man, however, needs to be told that learning any number of scientific facts from books cannot be called the study of the subject to which those facts relate, but can only be called picking up general information about the subject. It is well to have a stock of general information about many subjects apart from those which we study thoroughly; but general information can never be exact, and its acquisition ought to constitute the recreative, not the laborious, part of education. The study of a Greek grammar written in Latin will improve the student's knowledge of Latin, but will be worthless as a means of teaching him Greek, unless he follows it up by practice in reading that language. In like manner, the knowledge of any natural science, obtained only from a text-book, is scarcely valuable enough to warrant the consumption of much time in committing the book to memory, although its statements may be made with all the precision attainable by the use of mathe-

matics. The student may derive from it some real knowledge of mathematics, but little or none of the science which he has professedly been studying.

Few persons can undertake any serious study of astronomy, for want of the necessary appliances. There is, indeed, a purely mathematical branch of astronomy, which may be thoroughly mastered by the study of books alone, aided by actual practice in mathematical reasoning. But this theoretical astronomy, as it is called, is too difficult, except in its mere rudiments, for use in general education; and it is rather a branch of mathematics than of natural science, although its results are applicable to astronomical work.

For most students, then, the study of astronomy merely means the acquisition of such an amount of general information about that science as may serve to add to the rational interests and pleasures of their lives. The present work is accordingly intended rather to be read than to be learned by heart. The useful mental discipline which can be gained from books of general information chiefly consists in the practice of the arts of consulting them as works of reference, of correctly interpreting their meaning, and of properly estimating their authority. Although this practice cannot be extensively carried on at school, it is certainly injudicious to bring up young people to regard knowledge as consisting in the power of passing examinations which test only their memories, not their judgments.

But since these examinations in matters of mere general information are unfortunately in extensive use in our schools and colleges, teachers may find it necessary, if they use this book at all, to require their pupils to prepare parts of it for recitations of the customary

kind. To accommodate the book to this use, heavy type has frequently been employed to call attention to subjects on which questions may conveniently be asked; and in the first, or descriptive, portion of the book, the sections relating to the subjects which are most important, or best suited for recitations, have been numbered in heavy type. The sections of the eighth and following chapters are of necessity somewhat closely connected with each other; no distinction, therefore, has been made between them, and each chapter after the seventh will probably be studied or read without omissions, in any manner which may be preferred. No useful purpose, however, can be served by learning the meaning of azimuth (for example) by heart. If any one measures or calculates a few angles of azimuth in the course of his daily work, he will never forget what the word means; if he never has occasion to measure or calculate an angle of azimuth, why should he remember what it is? It is enough if he knows where to look for its meaning and its connection with other astronomical terms, on any occasion when he may require this knowledge. Accuracy does not mean omniscience, and indeed the attempt to acquire omniscience is certain to result in inaccuracy.

To facilitate the use of this book as a work of reference, its index has been made somewhat extensive, and frequent references have been inserted in the text from subsequent to preceding sections relating to associated topics. At the top of each page will be found the number of the section to which the first line of the page belongs. It may perhaps be found useful, after the book has been read, to spend a moderate time in studying it by subjects, with the aid of the index. Its lan-

guage has been made plain and clear to the best of the writer's ability, and perhaps with the result of making parts of it tediously diffuse; but it seemed better to run some risk of this kind than to fall into the opposite error. Mathematical and technical expressions have been avoided, so far as possible, in the first seven chapters; and illustrative geometrical figures have been replaced by verbal illustrations wherever this seemed practicable. For reasons which need not here be discussed, many learners acquire little from their early mathematical studies except an undiscriminating dislike of mathematics in general. Under these circumstances, they are disposed to pass over a mathematical explanation of any subject as hastily as possible, and to attach no strictly definite meanings to the terms used in it, to the manifest detriment of their reasoning faculties. On the other hand, students who have some actual working knowledge of mathematics may exercise themselves profitably in reducing an explanation given in ordinary language to a strict mathematical form, and illustrating it by geometrical figures of their own drawing, or, still better, by solid models of their own construction. Whatever they can do for themselves of this kind will teach them more, both of mathematics and of the subject to which they apply it, than they would gain from ten times as much work laid out in merely following the demonstrations of their text-books. Other reasons for the plan pursued in the present work are that too frequent references from the text to illustrative figures become vexatious to almost all readers, and sometimes result in making the student better acquainted with the figures themselves than with the subjects which they are meant to explain. Moreover, an explanation de-

pendent on an illustrative figure cannot conveniently be followed by a listener, if it is read aloud; this, however, is a comparatively slight drawback to the use of a school-book. As this work may be used by students who have never attained any facility in mathematical reasoning, or who have lost what they formerly had, the small amount of geometry required for the explanation of the telescope, and of the rudiments of practical and theoretical astronomy, is included in the eighth chapter, and in those which follow it. Any one who either remembers his geometry, or can work it out for himself, will be able to find neater methods of proof for the propositions employed in the fourteenth chapter than those which are there given because they seemed the most direct.

A good way of testing the learner's comprehension of any work of general information is to ask him questions, the answers to which are not contained in the work itself, but may readily be inferred from it. It is useless to publish many such questions with the work; because, if the learner knows them in advance, they are no longer tests of his knowledge, but only of his industry. The following questions may serve as specimens of the kind just mentioned. They may be useful after the whole work has been read; and the student should have the work before him to assist him in answering.

Why are the apparent paths of solar spots such as they are said to be in section 59?

Why ought each successive magnitude of stars to include more stars than the preceding magnitude? See sections 79, 457.

At what time of night may we expect that shooting stars will be, on the whole, most abundant, on the prin-

ciple that the forward side of a moving object is, on the whole, most likely to encounter other objects?

Why does the Earth's rotation prolong an eclipse of the Sun? Does this prolongation happen at all places on the Earth from which eclipses of the Sun are ever seen?

Does the Earth's movement in its orbit shorten or lengthen the time of a transit of Venus? of an eclipse of the Sun?

What are the poles of the prime vertical? of the equinoctial colure?

Why should Paramatta be said in the Almanac to be fifteen hours east, rather than nine hours west, of Washington?

It will also be well to accustom the learner to distinguish accurately between different uses of the same word. The following are examples of words used in various senses: altitude, aurora, corona, diameter, hemisphere, horizon, penumbra, phase, umbra.

Teachers who wish to exercise their pupils in simple astronomical calculations will find materials for this purpose in the sixteenth chapter. The precessions of stars, and hence their approximate proper motions, the periods of the synodical revolutions of the planets, the relative weights of equal masses at the surfaces of different bodies, and other problems of like character, may be studied by the aid of the data contained in this work; but of course some little knowledge of algebra and trigonometry must previously be had.

The only way of enabling a reader to estimate the authority of any statement placed before him is to accustom him to demand references to original authorities, and to test the correctness of every statement

whenever he can. This part of education is too often neglected; and grown men sometimes take any thing in print for gospel, and at other times are unreasonably sceptical. It would be well if readers required references throughout all popular works on science; but it would probably appear pedantic to fill this book with citations. Accordingly, it is only in the sixteenth chapter, which contains distinct statistical statements, that authorities are referred to. Care has been taken, however, throughout the book, to check, by means of original treatises, the statements derived from popular works; and it is hoped that few errors have escaped attention in the revision of the text. For the historical portion of the book, Delambre has been the chief authority consulted.

The illustrative lithographs have been copied, with Professor Winlock's permission, from the series of "Astronomical Engravings from the Observatory of Harvard College." On consideration, it has been thought best not to attempt any representation of nebulæ or comets. Good representations would be so expensive as to add too much to the price of the work; while ordinary ones, such as usually appear in popular works on astronomy, are of little or no service to the reader.

The thanks of the author are due to Professor Winlock for occasional assistance in settling doubtful points, and for many valuable suggestions.

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# OUTLINES OF ASTRONOMY.

## CHAPTER I.

### OBJECTS OF ASTRONOMY.

**1.** ALL the countries and oceans about which we learn by the study of geography make up the outside of that great ball, or globe, eight thousand miles thick, which is called the Earth. Eight thousand miles is so great a distance that we cannot well understand how great it is without the help of some comparison, like this. Suppose that, on some winter day, when the ground is covered with damp snow, we roll up a snowball a yard thick or more, so as to reach up to the waist of a man standing beside it. Let us make this snowball as round and smooth as possible, and then stick some rather small pins into it up to their heads. The heads of those pins will stand out as far from the snowball, with respect to its size, as the highest mountains in South America or India stand out from the Earth. So, too, if we make a little hollow in the snowball, just large enough to hold the head of a pin, that hollow will go as deep into the snowball as the hollows which contain the oceans go into the Earth, and deeper than the deepest mines go into it. Of course it would be very hard to make a snowball so perfectly round and smooth as not to have little lumps and hollows upon it many times larger than pin-heads; and yet, in spite of these little roughnesses, the ball would look smooth enough to any one standing a few steps away from it. So, too, the Earth's roughness, caused by its mountains and its valleys, both on land and under the sea, is really so slight in comparison with

its size, that we may regard it as a smooth round ball when we are considering the whole of it at once. We can now understand a little better what is meant when we are told that the Earth's diameter is eight thousand miles; for if a pin's head on a ball a yard thick is large enough to represent a great mountain on the Earth, we may imagine how small a house or even an ordinary hill would be when it was represented on the same scale. We see, besides, that the Earth's mountains cannot be represented in the right proportion by raised figures on a globe or map made on any ordinary scale.

**2.** The Earth seems to us to stand still; but, in fact, it is always moving along in much the same way that a ball is moving after it has rolled off the roof of a house and before it has come to the ground. Such a ball has at least three different kinds of movement at the same time. First, it is falling to the ground: but this is not all; for it does not drop directly downwards, as it would if it had been stopped just when it came to the edge of the roof and let go again. Instead of this, it has gained some headway by rolling down the roof; and while it is falling, this headway carries it farther and farther from the house. This is its second kind of movement. But besides falling and moving away from the house, it goes on rolling in the air just as it did on the roof. This third kind of movement is not so easy to see as the others, because it is generally too quick for the eye to follow. But if we take a rather large and light ball, — like a football, for instance, — place it near the edge of a smooth board a few feet from the ground, and then tilt the board just enough to make the ball roll off, we shall see that it turns over a little while it is falling. This can be seen more plainly if the ball is marked in some way; by pasting pieces of paper upon it, for example.

**3.** It is seldom that any ball moves in the air without having all the kinds of movement just described; that is, a dropping movement, a forward movement, and a rolling movement. The Earth is like any other ball in these respects; it is always falling, moving on, and rolling. How it

can be always falling without being stopped by something else, as a falling ball is stopped by the ground, will be explained hereafter. Another difference between the Earth and a falling ball is, that what the Earth moves in is not the air; for the air is really part of the Earth, and goes along with it. What the Earth moves in is not known. It is commonly called ether (the Greek word for air), because it is thought to resemble air in some respects; but the chief reason for believing that there is any such thing as this ether is that the light of the sun, moon, and stars takes time to come from them to us: and the easiest explanation of this is that the light comes to us through ether as sound comes through air, or as waves come along the water from the sea to the shore. Ether is a name which is also given to certain chemical liquids; but this use of the word has nothing to do with the other.

**4.** We know more of what the ether contains than of what it is. Many great globes, more or less like the Earth, are moving about in the ether. Some of them are known to be vastly larger than the Earth; others, again, are smaller. Besides these, the ether contains, as we have reason to think, a great deal of material resembling that of which the Earth is made, but scattered about instead of being collected together in masses. It is all in motion, however, so far as is known. All the knowledge we can get of these various contents of the ether belongs to the science of astronomy, — which also includes so much study of the Earth itself as is useful in making comparisons between it and other objects. For this reason, astronomy has much in common with geography, geology, chemistry, mechanics, optics, and other sciences. But the direct purpose of astronomy is the study of what lies outside of the Earth, and at a great distance from it. Every object of this kind is called a **celestial object**; what is part of the Earth, on the other hand, is called **terrestrial**.

## CHAPTER II.

### PROPERTIES OF MATTER.

**5.** EVERY thing which we perceive by means of our senses is called **matter**, when it is spoken of as one thing. But when we speak of the separate things which our senses make known to us, we call them **material objects**, or sometimes **bodies**, instead of matter. Material objects are either solids, liquids, or gases; and the same thing may be at different times solid, liquid, or gaseous, according to the circumstances in which it is placed. The most familiar example of this is furnished by water, which is often seen in the solid form of ice or snow, and is known to exist as a gas, although its shape cannot be seen when it is in that state; for when we see watery vapor, the water is in the form of little liquid drops, such as those which make up fog or mist. As for clouds, they may be made either of crystals of snow or ice, or of drops of water which are kept up for a long time by the air, just as dust is kept up by it. But besides the liquid water floating in the air, there is also a great deal of water forming part of the atmosphere itself, which is no more to be seen than are the other gases of the atmosphere, such as nitrogen. Steam, too, is a gas while it continues hot enough to remain invisible. We see, by the way in which water changes from one state to another, that what makes any material object solid, liquid, or gaseous, is partly its **amount of heat**, and partly other causes, which are to be learned by the study of natural philosophy and chemistry.

**6.** Solids, liquids, and gases may all be so hot as to shine, or give out light of their own. They are then said to be **incandescent**. An incandescent object may be on fire, as we say; but burning and incandescence do not always go together. A piece of lime, for instance, shines very brightly

when it is exposed to a great heat; but it does not burn: for what is meant by burning is permanent change as well as brightness and heat; and when the lime is cool again, it is still lime, as it was before. Melted metals also are often incandescent, and yet burn very little, if at all. In fact, few metals are commonly considered as combustible. We seldom see an incandescent gas, unless it is burning, because the particles of a gas are usually driven away by heat to some cooler place. Every flame is caused by burning gas; but most of the light of a flame is generally due to incandescent solid particles in it, not to the incandescence of the gas itself. An incandescent gas, whether burning or not burning, usually gives out much less light than an equally hot solid or liquid.

**7.** When any object shines by light of its own, and yet is not very hot, we call it **phosphorescent** instead of incandescent. Phosphorescence is not so usual a kind of shining as incandescence is; and when a celestial object shines by light of its own, we naturally suppose it to be incandescent, unless we can discover some proof that it is only phosphorescent. Incandescent and phosphorescent objects are sometimes called **sources of light**, or **self-luminous bodies.**

**8.** Many objects shine very brightly, and yet are neither incandescent nor phosphorescent. If a piece of polished glass or metal, for example, is held in the sunlight, it looks very bright when we see it from that particular place towards which most of the light that falls on it is reflected. All objects, so far as is known, reflect some light, although some reflect very little; and it is by means of this reflected light that we see most of the terrestrial and many of the celestial objects which are visible to us. Even gases reflect a little light. Some gases, like chlorine, have a distinct color, which enables us to see them; and the mixture of gases which makes up the Earth's atmosphere, or the air, as we commonly call it, has a blue tint, which can be seen when we look through many miles of it at a time. But if the floating solid and liquid matter contained in the air were all removed

from it, it would probably reflect very little light, and would scarcely look blue. This blueness of our atmosphere occasions the appearance which we call the sky, as will be shown hereafter.

**9.** Any material object may be hot or cold, luminous or dark; and probably, too, may exist under certain circumstances either as a solid, a liquid, or a gas. But there are other differences between material objects, which at all times distinguish them from each other. A piece of iron, for instance, differs in some respects from a piece of lead, whether the metals are solid or liquid, incandescent or dark and cold. Differences of this sort are called **chemical differences.** These chemical differences are accompanied by differences in the kind of light which incandescent or phosphorescent objects emit, or which other bodies reflect, so that if a celestial object cannot be otherwise examined, we can still find out something about its chemical properties by means of the kind of light which it sends us.

**10.** If we take bodies which have the same chemical properties, and are in the same mechanical condition, — that is, bodies which are equally warm, and as much alike as may be in every way which our senses can recognize, except that they may be of different sizes, — we then find that the largest is also the heaviest. By this we mean that it requires more exertion to lift a large piece of lead, for instance, than a small one; and that when it is lifted it can be made by proper means to do more work than the small piece while it is coming back to the level from which it was lifted. For example, the wheels of a large clock require a large weight to make them turn. This gives us a notion that the weight of a body depends on the quantity of matter which there is in it; so that it is supposed that a piece of lead has more matter in it, or has a greater mass, as we say, than an equally large piece of wood. But we should have no reason for believing this if we did not know that when we melt some lead and make two bullets of different sizes from it, so that neither has any hollow place in it, or can be shown to be less compact than the other, the

larger is always the heavier ; and that the same general principle applies to wood as well as to lead, and to everything else that we know of as well as to lead and wood. It is still easier to show that it applies to liquids and gases than that it applies to solids, because the particles of liquids and gases can move among each other so freely that there is apt to be less difference between different parts of a liquid or gas than between different parts of a solid. If we cut two pieces of wood from the same log, one of them may have a closer grain than the other, so that we can see a reason why it should weigh more, although it is no larger, than the other piece. But one pint of water is almost exactly like another taken from the same bucket. We should expect, therefore, to find, as we actually do, that if equal measures of a certain liquid or gas are weighed under exactly similar circumstances, one is as heavy as the other. Hence, when we find that a bottle full of quicksilver is very much heavier or harder to move than a similar bottle of water, we naturally suppose that the reason must be that quicksilver is denser than water ; that is, that the particles of the quicksilver are closer together than those of the water, so that more of them are contained in the same space. However, this supposition is not necessary to enable us to study the simpler portions of natural philosophy and astronomy. When two material objects are said to be equal in mass, what is meant is that it will take as much force to give one of them a particular movement as is needed to move the other just in the same manner and just as far. If we say that one object has more density than another, we mean that any portion of the denser object will have more mass than a portion equal to it in bulk of the other object, or that equal masses of the two objects will differ in bulk.

**11.** Every material object has some mass and density ; but how dense it is, compared with others of the same bulk, depends on several circumstances. Such circumstances are, first, chemical constitution ; a ball of lead has more mass than an equally large iron ball. Secondly, the density of a body depends on its compactness ; a loaf of bread is larger

than the flour and water it contains, which would weigh as much in any other form as they do in the form of bread. Thirdly, density depends on temperature, and, generally speaking, decreases as the temperature rises; a gallon of hot water is lighter than a gallon of cold water. Fourthly, the **state of aggregation** of the particles of a body affects its density; that is, when the body is a solid, it has not the same density as when it is a liquid, and it has still another density when it is a gas. On a wet day in winter, for instance, water often exists about us in all three forms, of ice, moisture, and invisible vapor; in all three forms it may have the same temperature, so far as the thermometer can show it, and it is the same thing chemically in all three forms. Moreover, we cannot see that the particles of a compact piece of ice, or of the vapor in the air, are not as close together as those of the liquid water. Still, the ice is not so dense as the water, and is denser than the vapor. It usually happens that a solid is denser than the liquid form of the same substance, but water is a well-known exception to this rule.

12. Facts like these have occasioned many notions to spring up about the way in which particles of matter are combined together in material objects, and the way in which matter is affected by heat. But a knowledge of the facts alone is sufficient to enable us to understand the principles of astronomy.

13. What has just been stated about material objects may be summed up as follows: —

All matter has some chemical constitution, mass, and density, and may be divided into parts: it may exist in different states of aggregation, that is, as solid, liquid, and gaseous matter; it may have more or less heat, and may be a source of light, or may only reflect light received from other sources.

14. Matter has other important properties, such as those on which depend the facts called electrical and magnetic phenomena. These properties have undoubtedly much to do with many events which come under the notice of astronomers; but so little is yet known of the nature of

their connection with such events, that it will be enough for us merely to notice their existence.

15. It may be thought that if matter is whatever our senses show us, then light and heat, for example, must be matter. This was, in fact, an old opinion, now given up. But, strictly speaking, we are informed by our senses, not of light and heat by themselves, but of bright and hot bodies. In the same way, we do not see colors by themselves, but colored objects. However, color, like many other words, is used in a variety of ways, which may easily puzzle people who are not good reasoners. The full meaning of such words can only be learned by learning all the facts to which they relate; and the student who understands this will not be likely to become confused by the imperfections of language, the use of which is the only way men have of telling others what they have observed.

## CHAPTER III.

### THE MATERIAL UNIVERSE.

**16.** EVERY material object is a part of the **material universe**, which is often simply called the **universe**. The difference between the universe and matter in its widest sense is that, in speaking of the universe, we think of the separate shapes and properties of the objects of which it is composed, but take no notice of these shapes and properties when we speak of matter. The extent of the universe is entirely unknown; but, as far as we are concerned with it, it is limited by the capacity of our senses. That is, the universe which we are to attend to in studying astronomy comprises every material object of which men know any thing, and no others.

17. There are many questions about the universe with which people sometimes amuse and sometimes perplex themselves, but which are not properly part of any science at all. There are others which are logical or mathematical, but not strictly astronomical questions. Still others are really parts of astronomy, but require so much knowledge of mathematics and logic that very few astronomers are capable of studying them; and other people, of course, cannot form any rational opinion upon them at all, or learn what is thought about them by those who can study them. It is curious that these questions, which can be comprehended only by a few unusually learned men, and which even those who can comprehend them cannot answer, are often supposed to be so simple that anybody may set himself to making guesses about them, and writing down his guesses with the notion that he is making discoveries in astronomy. Inquiries into the past history of the universe are often made by mere guess-work of this kind. It is natural that people should ask how the universe came to be what it now is; and the question may some day be

partly answered. But at present no distinct answer can be given; and even to understand the reasons which have led some distinguished astronomers to form opinions upon this subject, is out of the power of any one who has not thoroughly studied what is called theoretical astronomy. The less people can know, however, the more they seem disposed to conjecture; and one opinion or another about the origin of the universe, or some part of it, is maintained by many who have not the means of forming any sensible judgments at all upon such a question. In considering the history of astronomy, we shall have occasion to notice such opinions as deserve respect with regard to the condition of the universe before it assumed that structure which observation has shown it to have; but nothing is as yet generally admitted by competent judges to be known of this early condition.

18. There are interesting questions relating to the space which contains the universe; but they are too difficult for study, except by well-trained minds, and are not strictly astronomical, but rather geometrical questions. We occasionally see them discussed in a weak and unscientific way, which leads to no useful result. Of this kind are such questions as the possibility that the number of the stars is infinite in the strict sense of that word. In studying astronomy, as has been said, we must confine our attention to what can be actually observed.

19. One very common inquiry deserves some notice in a book of this kind, although it is one of that class of questions which have been described as not belonging to any science. Its object is to decide whether other parts of the universe than the Earth are inhabited; and whole books have been written upon this subject. It is a good subject to write about, because, as it is commonly handled, it has hardly any thing to do with facts, and a great deal with the sense in which people please to take certain words; and for the same reason it is not to be considered any part of science. Nobody can say exactly how much like a man a creature living elsewhere than on the Earth must be before it is fit to be called an inhabi-

tant of whatever place it occupies. To make the question plainer, suppose we alter it, and ask only whether a man could continue alive if he were suddenly removed from the Earth and set down somewhere else. It is not at all likely that he could, because we know that men are easily killed by what seem comparatively slight changes in the condition of things about them. Exposure to a climate to which they are unaccustomed, for instance, is enough to kill many people; and a climate which belonged to a place entirely removed from the Earth would not be apt to be as much like terrestrial climates as they are like each other. However, most of what has been written on this subject, so far as it has any distinct object, seems to aim at deciding whether any thing is known about the parts of the universe beyond the Earth which will enable us to judge whether we could live in any of them. So far as we can tell, the prospect is rather discouraging to any person who should wish to emigrate from the Earth with his present body, and should find means of doing so. We can see that there are some differences between the Earth and other places, and we do not know how many other differences there may be which we cannot see. But whatever we find out, we can always imagine something not yet found out, which would make it either possible or impossible, whichever we wish to believe, for us to live in any place we have not yet visited. Astronomical discoveries, then, will do very little to put an end to such a dispute.

20. Let us try one other way of putting the question. Are there any rational animals living in the universe except those upon the Earth? If astronomers could see any such animals, and find out the nature of their minds by their actions, the question could be treated as a matter of fact. The Moon is the nearest place in which such animals can be looked for; and an animal would have to be two or three thousand feet round before we could see it on the Moon plainly enough to tell what it was with any instruments we have at present. We are not likely, then, to make discoveries of this kind for some time to come. Meanwhile, some people argue as if animals

must grow in every place that is at all like the Earth, and others argue as if there could be none in any place at all unlike the Earth. Arguments of both these kinds are of no value in helping us to knowledge. If we knew just what there was about the Earth that made it a suitable place for animal life, then we could inquire whether such circumstances existed elsewhere. But we do not yet know why the Earth is the dwelling-place of man and other creatures; we only know that it is. We cannot say, then, that places like the Earth in many ways are fit for animals to live in; nor can we say that places unlike the Earth are unfit to support animals made to live in such places. If a fish could think at all upon the question, he would think, perhaps, that nobody could live out of the water. It is just as foolish for us to say that a rational animal could not be so made as to live in water or in fire. We see, then, that the question we have just been considering is not a scientific question at all; that is, it relates to a subject into which we have no means at present of inquiring in a rational manner. Knowledge is acquired only by studying such subjects as can be systematically investigated by the help of knowledge which we have already; it is not to be had by making guesses about any thing that comes into our heads. We need not blame people for making such guesses; but we are not to suppose that they are studying science when they are spending their time in that way.

**21.** We will now see what has actually been learned about the universe. The principal fact which we shall have to notice is that the more men study it, the greater is the variety of the objects they find in it. At first sight, all there seems to be in the universe besides the Earth is a number of bright specks in the sky, most of which are called **stars**; while two of them, called the **Sun** and **Moon**, are much larger than the rest, but seem to be small compared with the Earth. The stars seem much like each other before they have been studied carefully, and the Moon seems more like the Sun than like the Earth. But men know now that these appearances differ very much from the reality. There are many celestial objects which

cannot be seen even with telescopes, and indeed such objects are doubtless far more numerous than those which can be seen. The Moon is really one of the smallest celestial objects which are ordinarily seen, but yet its thickness is one-fourth as great as the Earth's. As for the Sun, one hundred and eight globes, each equal to the Earth, might be set side by side in a straight line within it. If the Earth could be set in the middle of the Sun, the Moon would be little more than half-way from the middle to the outside of the Sun, if it were placed as near the Earth as it actually is. How the Sun compares in size with the largest celestial objects which can be seen is not known exactly, for we do not yet know which of the stars is the largest; but there is reason to think that many of the stars are much larger than the Sun. But the stars differ much from each other in size and in other ways. Some of those which seem among the brightest are comparatively small, and resemble the Earth more than they resemble the Sun. These belong to the class of celestial objects called planets. Most of the stars which can be seen with the naked eye, however, are like the Sun in most respects, so far as is known. Very little, indeed, is known of the stars which resemble the Sun, for the nearest of them are at a vast distance from us. The thickness of the Sun has just been stated as one hundred and eight times that of the Earth; the distance between the Earth and the Sun is about one hundred and eight times the thickness of the Sun. Now the nearest stars which resemble the Sun are more than two hundred thousand times as far away from us as the Sun is. When we are aware of this, it is surprising that we have any knowledge at all of such remote objects.

**22.** From what has been learned about the celestial objects, it seems likely that if we could travel about the universe and examine the regions through which we passed as closely as we can the ground over which we travel on the Earth, the various objects which would come under our notice would be somewhat as follows. We should find the ether everywhere, not only between the Earth and other objects, but in them;

for this ether is supposed to be so very thin a gas, if it can be called a gas at all, as to penetrate all bodies as water penetrates a sponge. Our supposed journey would often take us through places where there was nothing but ether, and we might then perhaps get some more distinct knowledge with regard to its existence, and, if it exists, with regard to its nature, than we can obtain now. However, we may take it for granted, until more is known upon the subject, that we should find ether throughout the universe. If it has so little density that it can penetrate the densest solids, we can easily believe that it scarcely at all hinders the movement through it of the lightest celestial objects.

**23.** We should find moving about in the ether material objects of all kinds of chemical composition, of all kinds of density, and of all sizes which we can well imagine. Some would be solid, some liquid, and some gaseous ; some, probably, much colder than any terrestrial object ever is, and some, certainly, very much hotter than the hottest terrestrial fires. Here and there we should find great spaces filled with luminous gases, either incandescent or perhaps only phosphorescent. Such masses of gas are sometimes called clouds, but we must remember that they are unlike terrestrial clouds in many ways, and especially by being composed of gas, and not of liquid or solid particles. We should also find clouds, if we like to call them so, partly gaseous and partly liquid and solid. Some of these various kinds of clouds would have a round shape, like that of the Earth ; but many others of them, like terrestrial clouds, would have very irregular forms, and might be more or less divided into parts, so that it would be difficult to say whether we ought to count these parts as separate clouds or not. It is not certain that all these clouds would give out light ; there may be among them many which cannot be seen from the Earth, because they do not shine, and are not near enough to any luminous object to become visible by the light they reflect to us.

**24.** Besides these clouds, or masses of matter not closely compacted together, there are other masses which, whether

solid, liquid, or gaseous, are at all events more compact than those we have called clouds, and also much brighter. The Sun is one of these; and we may call them all suns. Perhaps there are bodies even larger than our Sun, which yet give out no light of their own. We should not call such bodies suns; and if they were compact and not cloud-like, we should regard them, even if they had no solid matter about them, as planets; or, in other words, as belonging to the same class of objects with the Earth. So far as is known, all these large and compact material objects, whether they are suns or not, are globular in shape, like the Earth; and it is reasonable to suppose that they all have the three principal kinds of movement which the Earth has; that is, that they are all falling, advancing, and rolling. When several of them are much less distant from each other than from other similar objects, they form what is called a **system**. The Sun, the Earth, and a number of other bodies, form a system known as the **Solar System**, because the Sun is the most important of the bodies which belong to it. But although the large bodies which compose a system are not so far from each other as from other systems, their distance from each other is great compared with their size; and so is usually the distance between any two systems, compared with the extent of either system. For instance, as we have seen already, it would take over a hundred bodies as large as the Sun to reach from the Sun to the Earth; and the distance of our system from the nearest system known to us is over two hundred thousand times as great as that separating the Earth and Sun. The objects we have called clouds often extend over more space than would suffice for many systems like the Solar System. Several systems may of course all form parts of one larger system.

**25.** All these large bodies, whether clouds, suns, or planets, seem to occupy a very small part of the space in the universe; and no doubt the spaces between them are seldom entirely vacant, or filled only by the ether. There is reason to think that, just as among terrestrial objects we find the

smallest the most numerous, so, too, celestial objects are scarce in proportion to their size. There are small gaseous clouds as well as large ones, and possibly many as small as terrestrial clouds, or smaller. There are certainly millions of little solid bodies moving about in our own part of the universe; and probably some of them are mere grains of dust. These little bodies are often of irregular form, like the stones and dust of the Earth; and they are so plenty that if we had not the air to keep them off they would make the Earth a very unsafe place for us. As it is, they sometimes force their way through the air and fall to the ground, although the air is a much more effective defence against these **aerolites**, as they are called, than would at first be supposed. Little objects of this kind often move in large swarms or clouds.

**26.** If, then, we could travel through the universe according to the supposition just made, we should very frequently meet little particles of matter in one form or another, and often come across moderately large material objects, or collections of small bodies; but we should find great bodies like the Earth only occasionally, even if our rate of travel was thousands of times faster than that of our locomotive engines; and bodies like the Sun would be very seldom encountered. But in looking at the sky from the Earth, these suns are almost all that we see; and it is only by noticing every thing we can, and attending carefully to the meaning of our observations, that we can show the smaller and darker objects in the universe to be as numerous as they are now considered to be.

27. Probably we cannot separate the material objects in the universe into entirely distinct classes, because, however we make the divisions, we always find objects partaking more or less of the character of two or three of the classes we have formed. Still, for the sake of convenience in studying and describing the universe, it is customary to classify the objects it contains, and we will accordingly consider them in separate classes. But we must remember that these classes are

artificial groups, which depend for their formation upon what we have learned up to any particular time rather than on the arrangements of nature. It must not surprise us, then, to find that as new objects are discovered, it often appears that they belong as much to one as to another of the classes which previous astronomers have formed; and from time to time it becomes necessary to change our classification so as to adapt it better to the new state of our knowledge.

**28.** At the present time the celestial objects are usually divided into five principal classes, which are the following: —

*a.* **Suns, or fixed stars.** These are large, globular, incandescent, and compact, though probably not solid, bodies. The name of fixed stars was originally given to all bodies of this class except the Sun, because, as seen from the Earth, they did not seem to change their positions with respect to each other from year to year. But this was merely because they are so far from us.

*b.* **Planets.** This name means wanderers, and was originally given to certain bright stars which were seen gradually to change their positions with regard to each other and to the fixed stars. But at the present time any body would be called a planet which gave out little or no light of its own, but was large enough, and always near enough to some sun, to shine by the light it reflected. No planets are known to exist except those which are seen by the light of our own Sun; but there is reason to think that other suns also have planets not too far from them to be regarded as belonging to the systems of which those suns are the chief members.

*c.* **Nebulæ.** This name means clouds, and is applied to the enormously large clouds, shining by light of their own, which have already been mentioned.

*d.* **Comets.** This name is derived from the Greek word for hair, and was originally applied to certain celestial objects which are occasionally seen for a time with streamers of light called tails attached to them. But now, any thing which looks like a nebula, but is near enough to us to have its apparent position among the other celestial objects continu-

ally changed by its motion, is called a comet. We know of no comets except those which occasionally approach our Sun and retire from it again.

*e.* **Meteors.** This name only means objects which are aloft or on high; it was not originally applied to any celestial objects except such as were seen only for a short time at once. But it has been applied to all remarkable appearances in the sky, such as comets and northern lights, as well as shooting stars. However, modern writers in English generally apply the name only to those comparatively small celestial objects which appear as shooting stars when they enter the Earth's atmosphere. Meteors, then, are any celestial objects too small to be conveniently classed as suns, planets, nebulæ, or comets.

29. It will be seen from this account of astronomical classification that it may be doubtful, as our knowledge of any celestial body increases, whether it is most properly to be called, for example, a sun or a planet, a planet or a meteor; in fact, we know of many planets so small that there is little to distinguish them from meteors. However, as all of them that are known are situated in one particular region of the Solar System, they are sometimes spoken of as forming a class by themselves, and are called asteroids; but they are commonly called planets, for reasons which will appear when they are more fully described.

30. Certain planets of a particular kind are called moons or satellites; but they need not be specially described at present.

## CHAPTER IV.

### SUNS, OR FIXED STARS.

**31.** IN describing the first of the classes of celestial objects named above, we will begin with our own Sun, since we have much more knowledge of it than of any other. But we shall see that this knowledge is, after all, very imperfect. It is not yet certainly known whether the Sun is solid, liquid, or gaseous; but the prevalent opinion at present seems to be that it is a great globe of gas, although the gases of its interior must be compressed and condensed to an extent which must make them very unlike any terrestrial gas with which we are acquainted. The exterior parts of the Sun are certainly gaseous. In other words, it has an **atmosphere**, as the Earth has: but the Sun's atmosphere is by far the larger of the two, even when viewed with regard to the bulk of the body it encloses; that is, the depth of this atmosphere is equal to a much greater fraction of the thickness of the Sun than the fraction of the Earth's thickness which is probably equal to the depth of the air. Another difference between the atmospheres of the Sun and the Earth is that all that part of the Sun's atmosphere of which we know any thing is a source of light, or shines by light of its own, like the Sun itself. But if this atmosphere were nearly as bright as the body of the Sun, then it would look like part of the Sun, while, in fact, its light is so faint compared with the Sun's that it can only be seen by instruments made purposely to examine it, except at times when the Moon comes between us and the Sun, and causes what is called a total solar eclipse. Then a great deal of the luminous atmosphere of the Sun can be seen without the help of instruments; but at the same time some reflected light is seen in the sky, which cannot well be distinguished from the light of the Sun's atmosphere, so that on

such occasions the exact limits of this atmosphere cannot be seen. Although the Sun's atmosphere is a source of light, the Sun would be brighter without it, for it cuts off more light coming from the Sun than it sends out itself. Near the surface of the Sun, however, it is so bright that it may actually increase the Sun's apparent magnitude.

**32.** It is not known whether the interior of the Sun, if we could see it, would be as bright as that part of it which we actually see, and call its surface. The matter presenting to us this surface, and lying within it, but comparatively near it, forms what is called the **photosphere** of the Sun. Most observers think that if it is solid or liquid matter, it is in the form of clouds; that is, it must consist of multitudes of little solid or liquid particles floating in gases of some sort, as our clouds float in the air. But the photosphere may be itself gaseous; and in that case it is composed of much heavier and more compact gases than those which constitute the atmosphere which has been mentioned. Another theory is that the photosphere, or part of it, is a liquid ocean covering the Sun. Whether solid, liquid, or gaseous, the photosphere is incandescent, as is obvious enough to other people than astronomers. The actual amount of light and heat which it sends out is too great, and our means of measuring it are too imperfect, to admit as yet of very accurate knowledge upon this subject. Still, some measurements have been made of the light and heat of the photosphere; and the difference between the heat of the iron which it probably contains, and what we call white-hot iron, is no doubt many (some astronomers think many hundred) times greater than the difference between our white-hot iron and cold iron. The light of the photosphere, too, is far more intense than any terrestrial light. Matter so intensely incandescent as that which makes up the photosphere cannot form the ordinary chemical combinations which occur among terrestrial substances; many, at least, of these combinations are found by experiment to be broken up by degrees of heat which can be produced artificially. When the simple kinds of matter or

elements which make up a compound body have been separated from one another by heat, they are said to be **dissociated**; and this state of dissociation is thought to be the ordinary condition of the matter of the photosphere and that part of the Sun's atmosphere which lies close to the photosphere. But it has been shown, by a method hereafter to be explained, that many chemical elements which are found on the Earth also exist as gases in that part of the Sun's atmosphere immediately surrounding the photosphere, where many other elements, of which we as yet know nothing, are also known to exist. The chemical nature of the photosphere itself cannot be observed with our present means. Probably, however, the photosphere, like the atmosphere about it, contains most if not all simple kinds of matter which appear upon the Earth, and others also, but not combined chemically as we find them here.

**33.** The Sun has undoubtedly all the three principal kinds of movement which have been said to belong to the Earth, and probably to all celestial bodies. But its rolling movement is the only important movement it has which we are as yet able to learn much about; and for the present we will consider this alone. In order to do so, we must first state distinctly what a rolling movement is. Strictly speaking, the movement we are to describe is rotation, and not rolling; for we commonly say that a ball rolls only when it turns round and moves forward at the same time. So, too, the wheels of a locomotive steam-engine may be said to roll upon the track; but the wheels of a stationary engine in a factory are not said to roll, but to revolve or rotate. Now the Earth and the Sun are properly enough said to roll, when we consider their various movements in connection with each other; but when we confine our attention to the difference between the movement of one part of either body and its other parts, it is customary to give the movement of the whole body the name of **rotation**. No part of a body, the whole of which is moving, can be absolutely at rest; but the peculiarity of rotation is, that by supposing any body which has only that

movement to be divided into small enough parts, we can find parts of it which move in a given time through a distance smaller than any which we please to name. For instance, the main shaft of a steamboat, although it moves along with the rest of the vessel, has only a movement of rotation when the motion of the vessel is left out of consideration. If, now, we consider the movements of the different particles of iron in the shaft, we see that some near the outside of it move farther in the same time than others not so near the outside. We see, too, that there must be some of these inner particles which move less than the millionth of an inch during one revolution of the shaft, and some which move less in the same time than any other very small distance we may name, provided that these particles are supposed to be sufficiently small. But however small we suppose them, the parts of each particle move at different rates; and so we may go on dividing them as long as we please, without finding one or any part of one which does not move at all. To make it easier to describe and study this movement of rotation, we suppose a straight line, without any thickness at all, drawn through the interior of the shaft, but not forming any part of it. This line must be so drawn that the particles of the shaft move less the nearer they are to this line; so that the line lies among those particles which move least, and may be considered as having no movement of its own. Such a line in any object which has a movement of rotation is called the **axis** of the object, or the **axis of rotation** of the object. An axis of rotation, then, is no part of the object which turns about it, but has a particular position in that object, without taking up any space there. It is, in fact, what every straight line is considered in geometry, — something having length and position, but not occupying space.

**34.** An axis of rotation does not always pass through the middle of the object to which it belongs. There are pieces of machinery, for instance, called eccentrics, because they turn about axes which lie out of their centres. But when an axis of rotation is not fixed mechanically, as are the axes of

pieces of machinery, but is free, like the axis of a bullet discharged from a rifle, or like that of any ball rotating in the air or the ether, then it must pass through the middle of the object which turns about it, unless the matter of which that object consists differs in density in different parts of the object. In every case of this kind the axis passes through what is called the centre of gravity of the object. This centre of gravity occupies such a place in any object of regular shape, that there is as much of the mass of the object in any direction from it as in the opposite direction. In most of the celestial objects of which we know any thing, the matter composing them is distributed evenly enough to make their axes pass through their middle points, so far as can be perceived.

**35.** But an axis may not always keep the same place in the object to which it belongs, even if it always passes through the middle of that object. When a ball rolls along the ground, its axis of rotation usually changes very frequently; that is, those parts of the outside of the ball which are turning slowest or quickest will not continue the same for any length of time. This is generally due to the roughnesses of the ground. When no other body disturbs the movement of a rotating body, its axis usually keeps its place. The Earth's axis, for instance, keeps its place perfectly, so far as can be discovered at present. There may be a little doubt whether the axis of the Sun is equally stationary, because different observers have not precisely agreed about its position; but it is likely that this is wholly due to our imperfect means of determining what that position is. However, the axis of a fluid or gaseous globe like the Sun, constantly agitated by irregular movements within it and in its atmosphere, may not be as steady as that of a comparatively solid and quiet body like the Earth. But if the place of the Sun's axis varies at all, the variation is slight, and we may accordingly consider the Sun as turning about a fixed axis passing through the exact middle of the globe enclosed in the photosphere. The **poles** of the Sun, like those of the Earth, are the points of its axis which lie in

its surface. Hence the nearer any part of the photosphere is to one of the poles of the Sun the smaller is the distance over which the Sun's rotation carries it in a given time; and the parts of the photosphere which are carried farthest by this rotation are those which lie about as far from one pole as from the other.

**36.** We now need names by which the poles of the Sun may be distinguished from each other. The Earth's poles are known one as the **north** and the other as the **south** pole; but if we are asked to explain the meaning of the words north and south, we can only say that the north pole of the Earth is the pole nearest some particular country, Greenland, for example, and that north means towards the north pole. But there are no fixed marks on the surface of the Sun, such as the continents and islands on the surface of the Earth. What marks there are do not last long at a time, as we shall see hereafter, and therefore are of no service in distinguishing between the poles of the Sun.

**37.** Again, the Sun's axis is not always in the same position with respect to that of the Earth. Sometimes one pole of the Sun and sometimes the other is the nearer to the Earth of the two. Hence we cannot distinguish between them, as we might do otherwise, by means of their comparative nearness to us. We must therefore make use of the following method.

**38.** Although no man, or at least no civilized man, has ever come very near either pole of the Earth, yet the study of astronomy has taught us in what part of the sky the various stars would be seen by an observer stationed anywhere upon the Earth or the Sun, and consequently at any one of their poles. For instance, we know that any traveller who reaches the north pole of the Earth, at any time within a few centuries from now, will have the star Polaris, known also as the North Star, nearly in his zenith. This means that it will be over his head, nearly as far as possible from the horizon. We know, too, what other stars he could see, in clear weather, while the Sun was below his horizon. Most of these stars

would remain the same from year to year. They would seem to change their places continually with respect to the terrestrial objects which might be in view, but they would not rise or set. At the south pole of the Earth, an observer would continually have in view another set of stars, scarcely any of which would be visible from the north pole; and he would scarcely ever see any of the others. The star Polaris would of course be beneath his feet, on the other side of the Earth.

**39.** Now if we could get a view of the stars from either of the poles of the Sun, we should likewise see constantly a particular set of stars. From one of the Sun's poles the star Polaris would appear to be about one quarter of the way from the zenith to the horizon; and although we should see some of the stars visible from the south pole of the Earth, and should not see some of those visible from its north pole, yet the greater number of the stars in sight would belong to the set seen from the Earth's north pole. At the other pole of the Sun we should not see Polaris, and most of the visible stars would belong to the set seen from the Earth's south pole. We may accordingly call that pole of the Sun from which Polaris could be seen the Sun's north pole, and the other its south pole; but in doing so, we must remember that we are using the words north and south in a somewhat different sense from that in which they are applied to terrestrial objects. When the region around the north pole of the Sun is in sight from the Earth, it is of course in that part of the Sun toward the northern sky.

**40.** The word equator is used with respect to the Sun much as it is with respect to the Earth. That is, the Sun's **equator** is the boundary line which we may suppose drawn between those parts of its surface nearer to its north than to its south pole, and those nearer to its south pole than to its north. An equator, like an axis, takes up no room, and is no part of the object to which it belongs. If we suppose the Sun divided into halves by its equator, the half which contains the north pole is called the **northern hemisphere** of the Sun, and the other its **southern hemisphere.**

**41.** Even if there were no stars in the sky, we could still distinguish between the north and the south pole of the Sun by methods of astronomy like those which show us what stars would be visible from places never visited by man. But if there were no stars to assist astronomers in their observations of the Sun, it is likely that the science of astronomy would now be so little developed that scarcely any thing would be known of the Sun's movements.

**42.** The rotation of the Sun is of the kind called **direct** rotation; an object turning the other way would have **retrograde** rotation. To make it clear what this means, let us suppose two wagons, one moving eastwards and the other westwards. The wheels of the first wagon will have direct, and those of the second retrograde, rotation. If we stand on the north side of the road, facing the wagons, the tops of the wheels of the eastward bound wagon will turn from right to left, and those of the other wagon's wheels from left to right; seen from the south side, the motions will be reversed. Now, if an observer could be placed outside of the Sun, near its north pole, so as to look towards the Sun along the line of its axis, then the side of the Sun which would appear to him to be uppermost would be turning from right to left, and accordingly we say that the Sun's rotation is direct. The terms direct and retrograde, then, as applied to the movements of celestial objects, depend for their meaning on the use of the words north and south. The movement of one object round another may be direct or retrograde as well as the rotation of a single object. In fact, if we consider the separate parts of any object which rotates, we see that some of them move round others. But every direct or retrograde movement must take place around some line which we can consider as running north and south. If we know of no such line, the terms direct and retrograde lose the meaning which they have in astronomy. Hence a figure drawn on paper will not be of much assistance in understanding them.

**43.** The time which the Sun requires for one complete rotation is about 25⅓ of our days. At first sight, this state-

ment seems to need less explanation than that just made about the way which the Sun turns. In fact, however, it is hard to get a really distinct notion of what a complete rotation is. When a wheel rolls along a track, we say that it has turned round once in the time which has been needed for every part of its rim to come once into contact with the track; and this notion is clear enough. But in forming it, we consider the track as stationary. When we remember that the track itself is turning along with the rest of the Earth, we see that there is a sense in which the wheel has not turned round exactly once in the time during which every part of its rim has once touched the track. In counting the rotations of any thing, then, we need something to reckon from, which we can consider fixed and motionless. But we know that the celestial objects are all in motion. If we assumed that the Earth had no motion except that of rotation, we should have to say that one rotation of the Sun occupied about 27 days instead of 25¼. This difficulty cannot be entirely removed except by acquaintance with practical astronomy; but the principle according to which the rotations of any celestial object must be counted may perhaps be partially explained by examples of its application to terrestrial movements.

**41.** Suppose a model to be made of a flock of birds in flight, showing the exact places of all the birds in the flock at some particular moment with respect to each other; and suppose another model to be made, showing in the same manner the places of these birds with respect to each other a few seconds later. We could then, by comparing the models, examine the changes which had taken place during those few seconds in the arrangement of the birds. To get a more definite notion of this comparison, let us suppose that we calculate separately for each model what would be called the centre of gravity (34) of the flock in the arrangement which that model represented, and put into each model a little mark of some kind, such as a small shot, to show whereabouts this centre of gravity is. We could then consider how any bird in either model was placed with regard to a line drawn from

that bird to the centre of gravity of the flock. To be accurate, we should have to draw the line from the same part of the bird in the two models. In one model, the bird might be facing towards the centre of gravity, and in the other facing away from it. We might then consider, if we pleased, that he had turned half round, or made half a rotation, while the birds were passing from one to the other of the arrangements represented by the two models; and if, instead of two models only, we could have one for any instant that we could name, we could then trace the gradual progress of the bird's rotation.

**45.** If the movements of celestial objects were apparently as irregular as those of a flock of birds, there would be little satisfaction in investigating them in any manner like that described in the preceding illustration, which is, of course, not intended to exhibit the actual method by which the Sun's period of rotation is determined. But it is a general principle that, when we have nothing that can be considered motionless from which to measure the movements of other objects, we must supply the want by using the positions of those objects with respect to each other at a given time as a fixed model, so to speak, with which their positions at other times may be compared. This principle is that on which we supposed ourselves to proceed in examining the movements of birds; and it is that on which astronomers must proceed in examining the movements of celestial objects. The laws which regulate the course of many of these objects are so well known that their effect can be calculated for any moment within many centuries, past and future. We might actually construct a model showing the directions of all these objects with respect to some among them at any such moment; but, in practice, the results of calculation are sufficient for our purposes, and no actual model is needed. Thus we can determine the appearance of the stars as seen not only from places we have never reached, but also at times before astronomy was studied.

**46.** It appears, from what has been said, that as we learn

more about astronomy we constantly have to correct our former conclusions about the movements of certain objects by means of the new knowledge which we acquire with regard to the relations of these objects with others. Thus, if we learn more hereafter than we now know about the Sun's movement among the other stars, we shall have to alter the figures which now express its period of rotation. But this alteration will be very slight indeed; and before it can be perceptible at all, we must have learned to observe the Sun and to determine its period of rotation with regard to the Earth much more accurately than we can at present.

**47.** The comparative thickness of the Earth and Sun has already been stated (21). From this it appears by geometry that the bulk of the Sun is over one million and a quarter times that of the Earth. The Sun, however, has been found not to exceed the Earth in mass as much as in bulk. Still, as the Sun would outweigh three hundred and twenty thousand bodies each as heavy as the Earth, its actual mass is as much beyond our distinct comprehension as if it were heavy in proportion to its bulk. The small comparative density of the Sun is obviously one of the reasons for supposing it to be a gaseous, or at least not a solid, body.

48. In speaking of the bulk of the Sun, we take into account only the globe lying within the outer limits of the photosphere, since this is all which can be readily seen. But our knowledge of the Sun's mass is derived from our observation of the influence it exerts upon the movements of other bodies, and this mass is accordingly that of the Sun and its atmosphere taken together. The mass of this atmosphere, however, must apparently form only an insignificant part of what we call the mass of the Sun.

**49.** Although it has long been known that the Sun is a globe, this fact is not immediately evident to any one who sees the Sun, but was originally learned only by putting together the results of many observations of other objects as well as of the Sun itself. It seems, when we look at it, like a round flat object, one side of which is turned towards

us. In fact, however, the various movements of the Earth and Sun are constantly changing our view of it, so that all the outer portions of the photosphere are brought in sight of the Earth at one time or another. The **disk** of the Sun is the name given to that part of the photosphere which we can see at any one time ; so that in speaking of the disk we are speaking of the Sun as it appears and not as it is. The edge of the disk is called the **limb** of the Sun. That part of the limb which rises and sets first is called the **preceding** limb, and that which rises and sets last is called the **following** limb. The words preceding and following are much more convenient than western and eastern for use in astronomy, because it is sometimes hard to tell what is meant by west and east. The **northern** limb of the Sun is of course that part of its limb between its preceding and following limbs on that side of the disk which is nearest the northern sky ; and the **southern** limb is opposite to the northern. We need not lay down any exact boundaries between these different limbs ; when we have to speak precisely, we use other terms. To a terrestrial observer stationed north of the Tropic of Cancer the northern limb of the Sun always seems uppermost at noon.

**50.** The Sun's disk is too bright to allow us ordinarily to look directly at it ; and when it is studied with telescopes, it is necessary to take care to protect the eyes properly against the light and heat which would otherwise seriously injure them. The safest way of doing this is to form an image of the Sun by means of a telescope upon a screen, and not to look through the telescope at all. When the disk is closely examined in this or any other suitable way, it is usually found not to be equally bright in all parts, although the darkest parts of it are undoubtedly very bright, and only appear dark by contrast with the brighter parts.

**51.** In the first place, the disk is on the whole brightest in the middle, and gradually grows darker towards the limb. On this account, a good photograph of the Sun generally makes it look somewhat solid, or like a globe, such as it

really is, instead of making it seem like a mere flat disk. This, however, is only an effect of light and shade, and the photograph of a round piece of pasteboard properly shaded would have the same solid appearance. In order to understand why the Sun's disk is brightest in the middle, let us first consider why the whole Sun usually seems brighter the higher it seems to be in the sky. When the Sun has just risen or is about to set, we look at it along the ground, so that between us and it there is a great deal of that denser and heavier part of the air which lies close to the Earth. But when we look at the Sun in the middle of the day, we are looking almost directly away from the Earth, so that the Sun's light reaches us after traversing only so much of the air as lies nearly above the place from which we look. The air grows thinner very fast as we go farther from the Earth, so that wherever its limits are, the great mass of it, at all events, lies within a few miles of the land and sea. Hence it appears that the higher the Sun stands in the sky the smaller is the mass of air between us and it. The air is not so transparent as we are apt to think it, so that a great deal of any light which enters it is stopped on its way, or, according to the usual expression, is **absorbed**; and the greater the mass of the air through which the light has to come, the greater is this absorption. This explains the comparative dimness of the Sun when seen near the horizon.

**52.** The Sun's atmosphere, like the Earth's, absorbs much light; and any part of it has undoubtedly more density and more absorbent power the nearer it lies to the photosphere. Now, when we look at the limb of the Sun, we are, in fact, looking about half-way round the photosphere from that part of it which seems to be in the middle of the disk to the part directly opposite, on the other side of the Sun. The light which reaches us from the limb must accordingly have passed along a considerable part of the photosphere through the denser portion of the Sun's atmosphere; while the light from the middle of the disk has come to us directly away from the Sun, and therefore through as little as might be of its atmos-

phere. The gradual darkening of the Sun's disk towards the limb is consequently due to the globular form and to the atmosphere of the Sun taken together; so that it would be partly, though only partly, true to say that a good photograph of the Sun looks solid because it is actually the photograph of a globe.

**53.** The shading upon the Sun's disk which has just been explained is darker in some places than in others no nearer to the limb. In many parts of the disk we usually see a mixture of brighter and darker specks, which present what is called a granulated appearance. The brighter specks have been compared to willow leaves and to grains of rice; a sufficient name for them, however, is that of granules. They differ in form at different times, and their nature is unknown. When a bright spot or streak large enough to be separately noticed appears upon the disk, it is called a **facula**.

54. Faculæ are seen for the most part near the limb, but not very close to it; while the ordinary granulation is best seen in the middle of the disk. This may be explained by supposing that the matter of the faculæ is no brighter than that of the photosphere, while the faculæ lie in a region outside of the photosphere and considerably beyond it, although we need not suppose them entirely disconnected from the photosphere. In this case the light from the faculæ near the limb would be much less subject to absorption by the Sun's atmosphere than that from the neighboring part of the photosphere, so that the faculæ would be separately seen. On the other hand, near the middle of the disk the comparative brightness of the photosphere would hinder us from seeing the faculæ separately. Close to the limb, again, the absorption of the light of the faculæ may be great enough to make it hard to see them. The matter of the granules probably also lies outside the main body of the photosphere, but is connected with it more closely than the faculæ are. Towards the middle of the disk we can look in between the granules and see the darker spaces among them, while

we see the granules near the limb from one side, so that each granule hides the space between it and the granule next to it on the side towards the limb. In the same way, we cannot see the valleys among a distant group of mountains ; but we could, if we were in a balloon above the mountains, so as to look towards their tops instead of their sides. But what faculæ and granules are, and how they are arranged, is still doubtful.

55. The darker specks on the Sun's disk are perhaps due to masses of absorbent vapors occupying cavities or hollows in the photosphere. Whether the matter of the photosphere is liquid or gaseous, or composed of clouds of liquid or solid particles floating in gases, it is no doubt in a very changeable and disturbed condition, with mountains and valleys forming and closing perpetually, like the mountains and valleys which we see in the great masses of cloud rising before a thunder-storm ; but these terrestrial clouds are of course much smaller than any which could be seen at our distance from the Sun.

**56.** A dark speck upon the Sun's disk large enough to be separately noticed is sometimes called a **pore**. This name seems to imply that the speck is a hole through the photosphere ; but in fact we do not know that it is so. A large pore is called a **macula**, or more often and more simply a **spot**. The solar spots are the most noticeable objects on the Sun's disk, which is seldom wholly free from them. A spot often consists of two distinct parts : a dark central portion, called the **umbra**, and a lighter portion surrounding the umbra more or less completely, and called the **penumbra**. The umbra is not always uniformly dark. Sometimes one portion of it is darker than the rest ; the name of **nucleus** has been given to any such unusually dark part of an umbra. Sometimes a whole umbra is called a nucleus, but this is not a good practice. The inner edges of penumbræ, or those edges which border upon the umbræ of the same spots, have been noticed to appear brighter, at least in some places, than their outer parts ; and this has been thought to result

from the crowding together of granules moving towards the inner edges of penumbræ from the parts of the photosphere around the spots to which these penumbræ belong.

**57.** The forms of solar spots are very various; and a spot often changes its form considerably in the course of a few days, sometimes even in a few hours. Occasionally, however, a spot retains for many days a nearly circular shape, a round umbra being enclosed in a ring of penumbra. Some spots consist only of penumbra, others only of umbra; others have both penumbra and umbra arranged in a manner more or less unsymmetrical; several umbræ are seen at times surrounded by a continuous penumbra. Spots very generally occur in groups; and a group of spots is sometimes large enough to be seen without a telescope. Bright streaks, called **bridges**, are often seen crossing spots from side to side, or projecting into them upon one side.

58. Solar spots are almost always more than twice as far from either pole of the Sun as from its equator; but a spot is seldom more than eight times as far from the pole nearest to it as from the equator. In other words, and using the term latitude with regard to the Sun as geographers use it with regard to the Earth, the region where spots abound in each hemisphere of the Sun is between the tenth and thirtieth parallels of latitude.

59. The rotation of the Sun causes the spots apparently to cross its disk from the following to the preceding limb. Since sometimes one and sometimes the other pole of the Sun is upon the disk, according to the situation of the Earth and Sun with respect to each other, the paths of the spots across the disk sometimes seem to be curved one way and sometimes the other. When both the Sun's poles are near the limb, the paths of the spots seem to be nearly straight. This happens early in June and December of each year. In March and September the paths of the spots seem most strongly curved, being in March hollow or concave towards the south, and in September towards the north. It is by careful observation of the apparent paths of the spots upon

the disk, and by calculations depending upon such observations, that we have been able to discover the position of the Sun's poles, and the time which one of its rotations occupies.

60. But the spots change their places to some extent with respect to each other, and consequently the period of the Sun's rotation as determined from the movements of one spot will differ from that determined from the movements of another. As a rule, the period of rotation is found to be shorter when determined from spots near the equator than when spots far from the equator are used for the same purpose. If there were spots enough close to the equator of the Sun to enable us to make use of them alone in determining the period of the Sun's rotation, they would make that period seem to be very little, if at all, more than 25 days; unless the rule just mentioned does not hold good in all parts of the Sun. We see, then, that no one knows precisely how fast the main body of the Sun turns upon its axis; for the only marks by which we can judge of the rate of this movement are not fixed upon the Sun. It is possible, indeed, that there are such currents of gas circulating about the Sun in the region of its spots as to make the rotation of that region decidedly different from the rotation of the Sun's interior portions. Particular spots may change their places with regard to others, either by their drifting about under the influence of gaseous currents, or by their irregular growth and dissolution; just as a terrestrial cloud may be blown along by the wind, or may seem to change its place because one side of it melts away and the other increases. These changes of places of solar spots are called their **proper motions**.

61. A group of spots is generally more or less surrounded and interspersed with faculæ; and solitary spots often have faculæ in their neighborhood. The faculæ preceding (49) spots are apt to be smaller and fewer, but brighter, than those which follow; and the largest umbra in a group of spots is apt to be on the preceding side of the group. When a circular spot is near one of the limbs, it looks oval instead

of round, so that when it is close to the limb it seems like a dark line drawn along the limb. This is an effect of perspective, like that which makes a window seem narrower when we look along the side of the house it belongs to than when we stand opposite to it. But besides this, the penumbra of a spot near the limb often seems to lie between the umbra and the limb, while when the spot is in the middle of the disk the penumbra is seen all round the umbra. Observations of this kind gave rise to a theory that an umbra is the bottom of a pit in the photosphere, the sides of which appear as a penumbra. But this theory is now less in favor than it was; and in a small book like this there is no room for an account of the different suppositions about solar spots which have been formed or renewed in recent times. The prevalent belief is that a spot is an appearance due to a mass of gases comparatively cool and having much power of absorbing light, which accordingly darkens that part of the photosphere between which and the Earth it lies. These gases very probably occupy some kind of hollow in the photosphere. A spot can be said to be dark only by contrast with the surrounding photosphere, much as a wire heated red hot in a bright flame is dark by contrast with the flame, and looks black when held between the flame and the eye. The darkest part of a solar spot is probably brighter than any incandescent terrestrial object.

62. The rotation of the Sun prevents any spot from remaining in sight more than about a fortnight at a time. But after passing out of sight on the preceding limb, spots often last long enough to reappear on the following limb; and they have been known to outlast eight or nine rotations of the Sun. Of course, however, it cannot be known that spots have not closed up or dissolved and new ones been formed in the same neighborhood while that part of the photosphere in which they occur has been turned away from the Earth. It often happens, in fact, that after a spot upon the disk has dwindled away entirely, a new spot is formed somewhere near the place of the old one.

**63.** The average number of spots visible at once varies from time to time. A **maximum** of spots is said to have occurred at any time when the spots were more abundant than they were for some seasons before or after; and a **minimum** of spots occurs when spots are comparatively very scarce, so that there are often days when no spots can be seen. A maximum of spots occurs about once in every eleven years; but two maxima are not always just eleven years apart. For example, there was one maximum in 1848; the next did not come till 1860; and the next came in 1870. A minimum of spots usually comes not half-way between two maxima, but rather nearer the maximum that is to come next than to the previous one. For example, the minimum between the maxima of 1860 and 1870 came early in 1867. About the time of a minimum the spots on the whole lie nearer the Sun's equator than usual.

64. Besides this period of eleven years, there is another longer period of variation in the numbers of the solar spots. But the spots have not been carefully observed for a sufficient time to determine the exact length of this long period. It apparently occupies five of the short periods.

65. The reason why spots are more abundant at one time than at another is still unknown. There are some grounds, however, for thinking that any large object, like a planet, not too far from the Sun, tends to diminish the spotted area of that part of the photosphere nearest it, and perhaps to increase the spotted area on the opposite side of the Sun.

**66.** The photosphere is too bright to allow us to see much of what goes on in the Sun's atmosphere between us and the disk. Even round the limb, where there is of course much of this atmosphere which has not the disk behind it, an ordinary telescope is prevented by the sunlight which our own atmosphere reflects and scatters in all directions from showing us any thing remarkable in the atmosphere of the Sun. But this difficulty has been overcome by the invention of the spectroscope, an instrument which can be so applied to a telescope as to enable us to learn much about the Sun's atmos-

*Plate I.*

Thompson & Bentley, Lith. 112 Wash. St. Boston.

The number of prominences represented around the disk of the Sun in the above view is probably much greater than the number of prominences ever actually visible at one time; but the form and height of each prominence are derived from actual observation. The granulation shown in the figure is coarser than that which is usually seen. A few faculæ appear near some of the spots close to the limb; and the two zones of spots are shown.

Tompson & Ramsay Lith. 112 Wash St Boston

The granulation of the photosphere, and the umbræ, penumbræ, and bridges of solar spots, are shown in this figure.

phere even when the disk is behind the part of it at which we look; and still more about it as it appears around the limb. In this way its chemical constitution has been to some extent discovered, as was said above (32).

**67.** Close to the photosphere, and everywhere enveloping it, there seems to be a layer of atmosphere consisting of vast numbers of metals and other substances in the form of gas. The matter of which the photosphere consists may be floating in this atmosphere (32), which may therefore not merely surround the photosphere, but be mingled with it. The heat of the Sun, then, is so intense that it keeps substances like iron not only melted, but actually boiling, all around it. Outside of this innermost shell of solar atmosphere is another in which many metallic gases exist, as well as others, although they are not at all times hot enough to give out light of their own. This part of the Sun's atmosphere has been called the **chromosphere**. Incandescent hydrogen gas seems to exist everywhere in the chromosphere, extending here and there as much as a fifth part of the Sun's whole thickness, or, in other words, over a hundred and fifty thousand miles, beyond the photosphere. Mountainous projections of the chromosphere of this kind, though not always so large, are called the Sun's **prominences** or **protuberances**. Other gases than hydrogen can often be perceived in these prominences, especially in such as have the form and appearance of jets of flame rather than of mountains, clouds, or wreaths of smoke. The whole chromosphere, as seen around the limb of the Sun, has usually a jagged or serrated outline, as if it were coated with small prominences, as a field is covered with blades of grass. But the smallest of these projections which can be seen from the distance at which we observe them must of course be many times larger than the great mountains of the Earth.

68. Magnesium, in the state of incandescent gas, is one of the chemical elements most frequently perceived in the chromosphere and its prominences, and is sometimes apparent around all or almost all of the Sun's limb. It would be

useless to enumerate the other substances proved or suspected to form part of the chromosphere, since our notions of its constitution are very imperfect and constantly liable to change in consequence of new observations.

69. The solar prominences are of a very great variety of forms, as appears from any of the drawings which have been made of them. Portions of the matter of the chromosphere are often seen detached from the remainder and floating in the atmosphere around it, or sinking towards it. Prominences often change their forms very rapidly, and even appear to explode and suddenly become dispersed into fragments; some, however, remain nearly unchanged for many days at a time. Prominences of a particular kind, the appearance of which seems to indicate that they have been formed by eruptive action, are found to be associated with faculæ; or, as some say, are faculæ themselves. That is, when the rotation of the Sun carries a facula off the disk, a prominence of this particular kind is generally seen on that part of the limb which the facula is presumed to be crossing. In the same way, the appearance of a facula which the Sun's rotation brings upon the disk is preceded by the appearance of a prominence of this particular kind on that part of the limb crossed by the facula.

70. It is commonly believed, although it is not yet proved, that by the use of the spectroscope, astronomers are often enabled to learn which way the objects they observe are moving, and even to estimate their speed. Certain spectroscopic observations have been thought to show that some of the solar prominences are whirlwinds of fiery gas. The gas on one side of such a whirlwind must of course be coming towards the observer, and on the other moving from him, provided that he is looking across the whirlwind and not along its axis. For instance, when we look down upon a spinning top, each part of it perhaps keeps always at about the same distance from us; but if the top is on a table, then the part of the top on the left hand of a person sitting before the table is coming towards him and the opposite part going

from him, if the string was wound in the usual way. The speed with which the whirling prominences are thought to turn is sometimes so great that their outer parts are carried more than a hundred miles in a second; and the movements of parts of protuberances of other kinds, especially when they seem to be scattered by some sort of explosion, are as quick, and even quicker. It is not certain, however, that the facts which have given rise to the belief in these movements have been correctly understood.

**71**. Before spectroscopes were invented, the prominences could only be seen during total eclipses of the Sun, when its disk is behind the Moon for a few minutes. At such times any large prominences which are then situated on the limb of the Sun can be seen without the help of instruments. Their color is usually pale red, or reddish yellow. This is because the strongest part of the light sent out by incandescent hydrogen is of a particular shade of red, and most of the light from the prominences is the light of incandescent hydrogen. When seen in the spectroscope, the prominences may be made to appear red, yellow, or blue, according to the manner in which the instrument is used. But it is most convenient to use it so as to make them appear red.

72. The prominences and faculæ are on the whole most numerous and brilliant in the same parts of the photosphere where the spots are most abundant (58); but they are not so strictly confined to these regions as the spots are, sometimes being seen near the poles of the Sun. Attempts have been made to determine, by means of faculæ and prominences, the rate of the rotation of parts of the photosphere beyond the spotted region; and so far as any thing has thus been made out, it would seem that the period of rotation is not far from 25 days for any part of the photosphere.

**73**. Part of the Sun's atmosphere certainly lies outside of the chromosphere; but no way has yet been found out in which this outer atmosphere can be examined except during the few minutes of a total eclipse. Little, therefore, is known about it, although a great deal has been imagined about it.

We are not yet certain how much of the light seen round the Sun during its total eclipses really comes from its atmosphere. This light is called the **corona**. It has often been photographed during total eclipses, and the pictures thus obtained at different times and places have enough likeness to each other to show that at least the inner parts of the corona actually belong to the Sun's atmosphere, or to some kind of shining matter surrounding the Sun and keeping about the same shape. Near the poles of the Sun there is comparatively little of this shining matter, and although there is more of it about the Sun's equator, it is most abundant in places between the poles and the equator, resembling in this respect the spots, faculæ, and prominences. It shines by light of its own, so that the corona does not wholly consist of sunlight reflected from gases or other kinds of matter (8). In some photographs of the corona, it appears to consist of two or three different masses of light mingled together, but distinguished by their differences of brightness. The innermost part of the corona appears as a ring of bright light, close to the limb, and not reaching farther from it than the prominences sometimes do. This, no doubt, belongs to what we may properly call the atmosphere of the Sun. As to the rest of the corona, so far as it is not occasioned by the Earth's atmosphere, no one knows yet whether it is due to an incandescent atmosphere of the Sun; to electrical action; to matter thrown out of the Sun, as our volcanoes throw out flame, smoke, and ashes; or, finally, to matter moving about in the Sun's neighborhood, but not to be regarded as forming any part of the Sun. All these suppositions have been made, but we must wait for much more knowledge of the Sun than we have now before we can say whether any of them are correct.

74. The heat of the Sun, like its light, is to a considerable extent absorbed by its atmosphere; so that the heat we get from any part of the photosphere depends on its distance from the limb at the time. Besides this, it has been found that the region about the Sun's equator is somewhat hotter

than regions nearer its poles. Other differences of temperature in different parts of the Sun have been suspected, but are not known to exist.

**75.** How the Sun came into its present condition, and how that condition is to change hereafter, if it changes at all, are questions on which much has been said and written; but they cannot be settled at present, and none but good mathematicians are really able to understand the arguments which there are for holding one opinion or another on any such question. We have no means as yet of knowing whether the Sun is growing larger or smaller, brighter or fainter, hotter or cooler. We cannot even determine accurately how much heat and light it sends us now, or how its heat and light compare with those of other celestial objects. Much progress has been made, however, in inquiries of this kind; and probably men will some day be able to follow the course of the Sun's changes so as to foresee what changes are to come next. What is certain now is that no changes have occurred in the Sun for several thousand years so great as to alter noticeably the condition of mankind.

76. We can determine the size of the Sun somewhat more accurately than we can determine the amount of its heat and light. Still, owing to the difficulty of deciding where the body of the Sun ends and its atmosphere begins, and to the stormy and unsettled condition both of the photosphere and chromosphere, we cannot measure the Sun with great precision, and some observers have fancied its shape to be somewhat irregular, and not that of an exactly uniform globe, or, in other words, of a sphere; while most astronomers think that so far as can be seen the Sun on the whole is exactly spherical. On account of this uncertainty of measurement, the Sun might actually grow larger or smaller for a long time before the fact could be discovered. If it is growing hotter, we should expect that to make it grow larger; but, on the other hand, its shrinking would keep up its heat, or even increase it. Its enlargement by the addition of matter from the surrounding parts of the universe might tend

to heat it, but might also give rise to effects of an opposite tendency within it. On the whole, then, when we see one theory or another advanced with regard to the future history of the Sun, it is safest to remember that the theory cannot, in the present state of human knowledge, be any thing more than a guess.

**77.** If other suns than that which has just been described could be thoroughly compared with it by means of astronomical observations, we might be able to answer some of the questions mentioned above. But the great distance of the other suns (24) makes it difficult for us to study them at all, and what we know of them is little more than their resemblance in some important particulars to the Sun of our own system. Every object commonly called a star seems to be one of these suns, except those stars the motion of which, with respect to the others, can be easily perceived by at most a few days' observation. It will be convenient, then, to use the word **star** only when we intend to speak of a sun. A shooting star, a morning star, or an evening star, is not a star at all in this sense of the word; shooting stars are meteors, and the objects called morning and evening stars are planets.

**78.** The number of stars which can be seen without the aid of any instrument depends of course on the strength of the observer's eyesight and the climate of the place where he is. The number of stars which can be seen from well situated places in the southern hemisphere of the Earth seems to be decidedly greater than the number visible from its northern hemisphere. Perhaps we ought to allow that as many as ten thousand stars may be seen by sharp-sighted people. But wherever we stand, the Earth cuts off our view of about half the universe at any one time, so that not more than about five thousand stars can be in sight at once. In most parts of the northern hemisphere, persons with ordinary eyesight probably cannot see more than 2000 of the stars above their horizon at any particular time. Many millions of stars can be seen with the help of powerful telescopes.

79. The difference in brightness which we notice between different stars may be occasioned either by their different distances from us or by an actual difference in size or brilliancy between the stars themselves. As we know the distance of very few stars, we cannot usually tell whether a bright star is larger than a faint one, or actually brighter, or only nearer to us. But on the whole, if bright and faint stars are evenly distributed through the universe at different distances from the Earth or any other object from which we choose to measure, then the effect must be practically the same as if the stars were all equally bright. That is, if we divide the stars according to their brightness into groups equally large, each containing some great number of stars, so that for instance the first group contains a thousand stars the faintest of which is as bright as any star not belonging to the group, while the second group takes in a thousand stars the faintest of which are as bright as any not belonging to either the first group or the second, and so on ; then it will be reasonable to suppose that the average distance from the Earth of the stars in any group will be greater than the average distance of the stars in any brighter group. In any actual grouping of the stars on this system we should make each successive group include more stars than that preceding it, for reasons which will be obvious to any one who is acquainted with geometry.

**80.** We know nothing of the bulk or size of any star except the Sun. But some notion has been gained of the masses of a few stars. The star Procyon, for example, is thought to have a mass eighty times as great as that of the Sun. If its bulk is proportionately great, its thickness must on geometrical principles be nearly four and a third times that of the Sun, and over four hundred and sixty times that of the Earth. There is nothing unlikely in this, but it cannot be proved, since Procyon, like the other stars, bright or faint, shows us no disk which we can measure. One proof of the good quality of a telescope is its making the stars look smaller, not larger, than they seem with a worse instrument.

The apparent disk of a star is only a blur of light which is reduced to a little dot by a good telescope when the air is clear and quiet. No star, even if it were considerably nearer to us than the nearest yet known, could show us a real disk, by measuring which we could learn the bulk of the body to which it belonged, unless its thickness was at least thirty or forty times that of the Sun. If there are any stars much over one hundred times as thick as the Sun, they are not among those which are nearest to us; and this is all which we know of the bulk of the stars.

**81.** But in spite of this, a bright star always looks larger than a faint one, just as a bright flame would look larger than a faint flame which was really of the same size with it. Hence astronomers speak of the **magnitude** of a star when they really mean its brightness. The stars which can be seen by ordinary eyes without any instrument are divided into six magnitudes. That is, a few of the brightest stars, although they differ much in brightness from each other, are all said to be stars of the first magnitude; then a larger number of stars, somewhat fainter than those of the first magnitude, are called stars of the second magnitude; the stars of the third magnitude are still more numerous and fainter; and we may go on classifying the stars in this way as long as we choose. Any telescope, even a small opera-glass, will show us many stars fainter than the sixth magnitude, and the better our telescopes are the more magnitudes of stars come into view, so that with the best instruments now made about twenty magnitudes of stars can be seen. After the first few of these classes, called magnitudes, have been formed, there is no difficulty in finding stars enough, all about equally bright, to make up each succeeding magnitude. But of course there are many stars, however we arrange our magnitudes, which will belong as much to one of two successive magnitudes as to the other. For instance, a star may be rather fainter than most of those called sixth magnitude stars, and yet rather brighter than an average star of the seventh magnitude. This does not prevent the classification

of stars into magnitudes from being convenient for many purposes; and when a star comes between two magnitudes, its degree of brightness may be indicated by naming both magnitudes. Thus a star of the magnitude 2.3 is between the second and third magnitude, but nearer the second than the third; while the magnitude 3.2 is nearer to the third than the second magnitude. In this way of writing magnitudes the dot is not a decimal point, but only separates the two figures. Sometimes, however, astronomers divide their magnitudes into tenths, so as to have ten times as many classes of stars as there are in the system just explained; and then a star marked 3.2 would be one belonging to the magnitude three and two-tenths, or in other words, fainter than a third magnitude star, not brighter, as it would be according to the other system.

**82.** Most stars of the first magnitude, and many of the second and third magnitudes, were named by ancient observers. Besides naming particular stars, early astronomers also gave names to groups of stars, called **constellations.** In course of time, however, constellations came to mean rather regions of the sky than groups of stars, just as a state means in geography rather a piece of land with certain boundaries than the people who live there. Many of the names both of stars and of constellations which are now in common use in the English language were originally Latin or Greek words; but several of the stars have names derived from the Arabic. Particular stars are often denoted only by the names of their constellations, with numbers or letters from the Greek or Roman alphabet prefixed, in order to distinguish between stars of the same constellation. But in modern times the place in the sky in which any star is seen from the Earth can be so briefly and accurately stated, that we can often dispense with any names for stars except the figures which point out these places. The first magnitude stars most familiar to people living about half-way between the north pole of the Earth and its equator are as follows: they may be divided into two groups, according to the time

of year at which they are most likely to be noticed. But the place where any star is seen changes with the time of day as well as with the time of year.

*a.* **Stars chiefly visible in winter evenings.** Sirius, the brightest of all first magnitude stars, is seen in the south-east early in January evenings. As the season advances, it is seen more towards the west at the same time of day, and late in spring we lose sight of it in the south-west. Near Sirius, and north of it, but farther west, is the constellation called Orion; its brightest stars, Rigel and Betelgeux, are of the first magnitude. Rigel is bluish white, like Sirius, and is in the southern part of the constellation; Betelgeux is reddish, and farther north. Apparently not far from this star, and somewhat west of it, is another red first-magnitude star, Aldebaran. Procyon seems rather more distant from Betelgeux than Aldebaran is, and in the opposite direction; it forms one corner of a great diamond-shaped figure, with Sirius, Rigel, and Betelgeux at the other corners. Capella lies considerably to the north of Aldebaran and Betelgeux. It is brighter than any of the stars just named except Sirius. East of Capella are two rather bright stars, Castor and Pollux. Pollux is the brighter of the two; Castor is hardly bright enough to count as a first magnitude star. Regulus, a star still farther east, visible later in winter evenings, is also faint for a star of the first magnitude.

*b.* **Stars chiefly visible in summer evenings.** The brightest of these is Vega, which is seen in autumn evenings nearly overhead; earlier in the season it appears in the north-eastern sky. It is as bright as Capella, or brighter. In the same region of the sky is Arided, a star about as bright as Castor or Regulus. Arcturus seems farther south and farther west, in autumn evenings, than Vega; in the evenings of spring it must be looked for in the north-east. Its color is slightly reddish. Spica is farther south than Arcturus. It is seen in early summer about where Sirius is seen late in winter. Altair is south of Vega and east of Arcturus. It is the middle star of three in a line with each other. An-

tares is a reddish star seen low in the south in the evenings of July and August; and Fomalhaut appears in about the same quarter in autumn.

83. The remaining stars of the first magnitude, Canopus, Achernar, and three stars in the constellations of the Centaur and the Cross, are at present always out of sight from places on the Earth far north of its equator.

84. It is not difficult, since there are so few stars of the first magnitude, to learn to recognize all which come in sight. They are most easily distinguished early in the evening, or by moonlight, when none but bright stars can be seen. Those which are in sight on any clear evening can then be used as guides in finding the names of other stars by the help of a globe or map; but unless some stars are already known, it is often troublesome for a beginner to learn the use of maps of the sky.

85. Planets may be mistaken for stars of the first magnitude until they have been watched long enough to discover their movement among the stars; but no planets seem to pass near any stars of the first magnitude except Aldebaran, Castor and Pollux, Regulus, Spica, and Antares.

86. Regulus, Arcturus, Spica, Fomalhaut, and Achernar, as seen from the Earth, do not seem to lie near the Milky Way, as do all the other stars of the first magnitude.

**87.** The name of the **Milky Way**, or Galaxy, is given to a whitish strip or belt of the sky, one part or another of which is generally in sight on any evening when the Moon is not too bright. The Milky Way is much wider in some parts than in others; and its outline is irregular. It is made up of great numbers of little stars, too small to be seen separately without a telescope. Not only stars of the first magnitude, but also other bright stars, are more abundant in those regions of the sky crossed by the Milky Way than they are elsewhere.

88. The subject of the arrangement of the stars in the sky, especially with reference to the Milky Way, has occupied the attention of many astronomers. Attempts have been made

to determine the shape which the whole group of visible stars taken together would have to observers who could look at that group from the outside instead of from a place within it like the Earth. But no satisfactory conclusion has yet been reached, although a theory long prevailed that the group is shaped somewhat like the letter Y, the place of the Sun being in the stem of the letter, near the fork. But this is doubtful.

**89.** Here and there in the sky, but chiefly in the Milky Way, and near it, we see stars forming **clusters**; and it is reasonable to suppose that the stars of each cluster form a system (24), although each of these stars is very probably the chief member of a smaller system. But we cannot feel sure that all the stars of each cluster belong to the same system, because two stars may be seen nearly in the same part of the sky, and yet one may be many times as far from us as the other is, just as the tops of two hills often seem close together when we are at some distance from them, but far apart when we have climbed the nearest of them. The stars of any cluster which can be seen without a telescope must be very far from each other to be seen separately at all; still, such clusters, or parts of them, may really be vast systems. One of the most familiar clusters of this kind is that called the Pleiades, visible near Aldebaran. Six stars can be seen in this group by most people, and ten have been seen by unusually good eyes. But even a small telescope will show many more. Aldebaran itself is the chief star of another group called the Hyades. Between Pollux and Regulus is another cluster called Præsepe, which looks like a whitish speck in the sky, its separate stars not being seen without a telescope. But the most remarkable clusters are some which can only be seen with good instruments. In these, hundreds and even thousands of stars seem to be gathered together into sparkling heaps, like the little crystals in a handful of snow. We can scarcely doubt that such clusters are really systems; and some have thought that they might lie entirely outside of the great group to which the Sun and the brighter stars, as well as those of the Milky Way, have

been supposed to belong. Sometimes this group has been called our universe; and the clusters thought to lie outside of it have been spoken of as separate universes: but this is a confused way of speaking, even if there are such outlying clusters, and we do not know that there are.

**90.** We should be sure that the stars of a cluster really belonged to the same system if we saw them gradually move among each other in such a way as to show that the movements of each depended more on the places of the others with respect to it than on the places of stars outside of the cluster. But such movements would be so intricate that we could not well understand them if they had been seen; and the places of stars belonging to clusters have not yet been observed accurately for a sufficient number of years to show us what changes occur in them. But when two or three stars only seem close together in the sky, it often happens that by watching them for a few years we can tell how they move with respect to each other; and we already know of several systems, each consisting of two or three suns. It is likely enough that these suns have many planets near them and belonging to their systems; but this is uncertain.

**91.** When two stars seem so close together that they appear as one star until the distance between them is considerably magnified by means of telescopes, they are said to form a **double star**. A double star is optically double, when the two stars which compose it are really far apart, and only seem near because one of them lies nearly between us and the other. When they belong to one system, they form a physically double star, or, as we often say, a **binary** star. Sometimes, but seldom, a star is said to be double even when we need no telescope to separate it into two. A rather faint star seen near Vega, for instance, appears double to many people. A good telescope shows that each of the two stars which make it up is itself double, and that there are several faint stars between the two pairs. The whole group is sometimes spoken of as a double-double star. We also speak of

any three stars seemingly near each other as a triple star; a close group of four stars may be called a quadruple star; and any close group of stars may be called a multiple star.

92. The separate stars which make up a double, triple, quadruple, or multiple star, are called its components; and the fainter components of such a star are generally called the companions of the brighter. Sirius and Procyon have faint companions, which are interesting, because they seem to have more effect on the movements of the stars they accompany than we should expect. Hence, these faint stars have been supposed to be in reality large bodies, but comparatively dim ones. The companion of Procyon is thought to have seven times the mass of our Sun. The mass of a star can be calculated only by means of the observation of its movements with respect to some other star of the same system with it. In such calculations our distance from the stars observed must be taken into account.

93. All the stars, we may take for granted, are governed in their movements by each other's places and masses; but the general movements among them which are brought about in this way must be far too complicated for us to comprehend at present. All that has yet been learned about these movements relates mainly to the way which the Solar system is moving; and all we know of this particular movement is that at present it is towards those stars which belong to the constellation (82) Hercules. There has been some speculation about a supposed revolution of various stars, including the Sun, about some centre near the Pleiades. But on this subject we have as yet no knowledge. The movement which each star seems to have in the sky among the other stars is called its proper motion. These proper motions are slow, however quick the actual movements of the stars may be, because we look at them from so great a distance. Thousands of years must pass before the general appearance of the evening sky can be changed by the proper motions of the stars.

94. If the spectroscope shows us any thing of the move-

ments going on upon the Sun, we may expect it to show something of the actual movements of other stars with respect to the Sun (70). By spectroscopic observations, the conclusion as to the movement of the Solar System already derived from the proper motions of the stars has been confirmed. Arcturus, for instance, appears to us near the constellation Hercules, while Sirius lies on the opposite side of the Solar System. Some astronomers who have studied these stars with the spectroscope inform us that the distance between Arcturus and the Sun is lessening, while the distance between Sirius and the Sun is increasing at the rate of from 10 to 30 miles in a second. But Sirius, like the other stars, is so far from us, that its distance may continue, and, perhaps, has continued to increase at this rate for centuries, while its brightness remains seemingly unchanged. Some time or other, however, if the space between Sirius and the Solar System constantly grows larger, we may presume that the star will seem faint to terrestrial observers, and finally disappear from their sight. It must be remembered that we know at present only that certain observers have concluded its distance to be increasing at the time of their observations, not that it has always been increasing.

95. Observations with the spectroscope have also confirmed the belief previously grounded on the brightness and remoteness of the stars, that they are bodies resembling the Sun (28). It has been shown that, like the Sun, they have photospheres surrounded by atmospheres capable of absorbing light of certain kinds; and that there is reason to think that in many ways their chemical properties are like those of the Sun and of terrestrial bodies. In particular, hydrogen gas is believed to form part of the atmosphere of many stars besides the Sun; and around some brilliant white stars like Sirius, hydrogen is thought to be very abundant in a greatly condensed condition. Some reddish stars, again, have been supposed to show by the nature of their light that their photospheres are more spotted than that of the Sun.

But the use of the spectroscope in astronomy is too recent to allow us as yet to draw many positive conclusions from the numerous and interesting observations made with it.

96. Without the spectroscope, we can see no difference in the light of different stars, except their differences of color, which are not striking enough to attract much attention from ordinary observers. Some stars, however, visible only with the aid of telescopes, are said to have very brilliant colors. A cluster in the constellation of the Cross is described by Sir J. F. W. Herschel as containing eight stars colored with various shades of red, green, and blue, so as to give the whole group the appearance of a rich piece of jewellery. The components of many double stars are described as brightly colored; this may be partly, but is not wholly, the effect of contrast between the tints of objects seen close to each other.

97. Notwithstanding the distance of the stars, the heat we receive from them is in many cases enough to be measured; and it is likely that if no heat came to us except from the Sun, the temperature of the Earth would be much lower than it is. But the heat received from any one star of even the first magnitude is of course trifling. More observations than have yet been made of the heat of the stars are needed before our knowledge of its amount can be considered exact. Measurements of this kind are made with delicate electrical instruments called thermopiles, which are attached to telescopes when used to determine the heat received from stars.

**98.** The brightness, or, in other words, the magnitude, of certain stars varies from time to time. Such stars are called **variable**. Their changes sometimes extend over many years, and in other cases are completed in a comparatively short time. One of the most interesting variable stars is Algol, in the constellation Perseus. It is ordinarily a star of the second magnitude; but at intervals of nearly $2\frac{7}{8}$ days it diminishes to the fourth magnitude and again increases to the second, these changes occupying about seven hours on each occasion. Since $2\frac{7}{8}$ is contained not quite 7 times in 20,

it follows that if Algol is noticed to be faint on any evening, it will again appear so on the twentieth following evening. But as this calculation is not strictly accurate, it will not serve for many repetitions of the star's variation. A more precise statement is given near the end of this work. The frequency of the variation of Algol, and the fact that it is never so faint as to be invisible, while its changes are still great enough to be easily perceived, enable every one to see for himself that it really varies. It appears from the northern hemisphere of the Earth in autumn evenings in the north-eastern part of the sky, and may be found without much trouble by means of any map of the stars.

**99.** Mira, the first star which was discovered to be variable, cannot be seen without a telescope when it is faintest, but is even brighter than ordinary second magnitude stars at the time of its greatest brilliancy. But as it is over 331 days in going through its changes, they are not so readily noticeable as are those of Algol.

100. A variable star in the constellation Argo, which is surrounded by a nebula, and has attracted much attention from astronomers, is sometimes of the first magnitude. The course of its changes has not yet been fully made out. This star is not in sight from places on the Earth far north of its equator. Betelgeux, one of the first magnitude stars above mentioned, is variable; but it never becomes as faint as an ordinary star of the second magnitude.

101. The cause of these changes in the brightness of stars is unknown. One of the most likely conjectures with regard to them is that they result from the periodical interposition of dark bodies of some kind, such as planets, or swarms of meteors, between us and the stars which appear variable. It has been thought, too, that the regular recurrence of the maxima of solar spots (63) may make it proper to consider the Sun a slightly variable star; and other stars may vary more from similar causes.

**102.** Stars have occasionally appeared where none, or, at all events, where none nearly as bright, had before been seen,

and after a time have disappeared again. Such stars are usually called **temporary**. There is no record of the appearance of any star which afterwards continued permanently bright. Temporary stars may be only variable stars with long intervals between their periods of greatest brightness. The brightest of all recorded temporary stars, which was for a short time far brighter than Sirius, and could be seen in the daytime, made its appearance in 1572 near the constellation Cassiopeia, disappearing altogether early in 1574. It has been suspected to be the same object which produced similar appearances in that part of the sky in the years 945 and 1264. If this suspicion is well founded, it should appear again before the close of the present century.

103. On the other hand, a faint star in the constellation Corona Borealis appeared rather bright in 1866, and observations of it made at that time with the spectroscope were thought to show that its brilliancy was due to the existence about it of incandescent hydrogen in unusual quantities. A conflagration of this kind, if the expression is allowable, may not return at any regular intervals, and any star the magnitude of which thus is irregularly altered would not perhaps be properly described as variable.

104. The colors of stars may vary as well as their magnitudes. Sirius, for example, was called a red star by early observers, but is certainly not red now. The temporary star of 1572 changed its color repeatedly before it disappeared.

105. Although our knowledge of the stars is still scanty, the observation of their apparent arrangement in the sky has been the means of giving us a great deal of information about the Earth itself, and the large bodies comparatively near it. It often happens in many studies, as in the study of the stars, that when we do not succeed in learning much at once about the subject which we directly inquire into, we yet find the little which we can learn about it useful to us in other pursuits and in ways which we could not have guessed beforehand.

106. The twinkling, or scintillation, of the stars is occa-

sioned by the Earth's atmosphere, through which their light comes to us. It depends on the fact that the stars are too far from us to show us any disks, but the exact nature of the variations of light called twinkling is not known. The air absorbs starlight as well as sunlight, so that a star near the horizon twinkles more and looks fainter than one of the same magnitude higher in the sky. The larger planets twinkle less than ordinary stars, because they show us disks, although these disks are too small to be recognized without a telescope.

## CHAPTER V.

### PLANETS.

**107.** THE name of **planets**, as has been said (28), is given at present only to certain bodies belonging to the Solar System (24). These bodies resemble each other in the following ways.

*a.* We see them by means of the sunlight which they reflect, not by light of their own. It is possible, indeed, that a few of them may be incandescent to some extent; but even if this is the fact, there are probably clouds surrounding these planets which cut off from us most if not all of their light; so that the light which they send us is mainly sunlight reflected from their clouds.

*b.* They never change their distance from the Sun very greatly; that is, no one of them is much over twice as far from the Sun at one time as at another.

*c.* They seem to be compact bodies, and not mere clouds of dust or vapor. Indeed, none of them are commonly supposed, like the Sun, to be in the state of gas, however condensed; but several of them may be mainly liquid bodies.

**108.** In many respects, and especially in size, the planets differ greatly from each other. A few of the largest of them are known to be globular in shape, like the Earth; the rest are so small that they appear like faint stars, and show us no disks by which we can judge of their shape and size. The bulk of such planets can only be imperfectly estimated by the consideration of their distance and brightness; their shapes are unknown; and their masses cannot usually be separately computed. Some of these small planets are the **satellites** of larger planets; that is, they always remain near the large planets on which they attend, so as to form with them little systems of their own, although such little systems are only

parts of the Solar System. Some satellites, however, are large bodies, and show us disks. The Moon itself is the satellite of the Earth. Its disk is large because it is near us, not because it is a very large body. Small planets which are not satellites are sometimes called **asteroids**; all of them which are known as yet are always at a greater distance from the Sun than that of the planet Mars, and at a less distance from it than that of Jupiter. More asteroids are discovered every year; at the end of the year 1873 the number of known asteroids was 134.

**109.** The names of the principal planets, in the order of their distances from the Sun, are as follows: Mercury, Venus, the Earth, Mars, Jupiter, Saturn, Uranus, and Neptune. Of these planets the four named first, which are always nearer the Sun than are any of the asteroids, are small compared with the other four; and only one of them, the Earth, is known to have a satellite. The four planets beyond the asteroids are large, and all of them have satellites, Jupiter and Uranus being known to have four each, and Neptune one. Eight distinct satellites of Saturn have been discovered, and the planet is surrounded by a ring, which is now generally thought to be made up of swarms of little satellites. Some observers have suspected that Uranus and Neptune also have rings; and of course additional satellites of any planet may be discovered hereafter. Venus, the Earth itself, Uranus, and Neptune have been thought by various astronomers to have satellites, in addition to those mentioned above; but no such additional satellites are known to exist.

**110.** What has been learned about other planets than the Earth relates chiefly to their movements. The fact that they appear to us to move about among the stars gave them, as has been said (28), their name of planets, and caused men to watch them more closely than any other celestial objects except the Sun and Moon. To show how thoroughly their courses in the sky have been studied, it has been correctly stated that we can now tell just how a telescope should be placed, so as to be pointing directly at Jupiter, for instance,

at any particular moment that can be named within a hundred years to come.

111. The words real and apparent are often applied to different sorts of movement with so vague a meaning that the explanations in which they are used can scarcely be understood. Astronomers are not in the habit of using them, but more commonly speak of motion in right ascension and declination, motion in an orbit, and so on. Such expressions have an exact meaning, and so has the phrase "apparent place," as used by astronomers. But this exact meaning cannot be comprehended by those who are only beginning the study of astronomy; and we so often find real motions and apparent motions mentioned in accounts of the bodies belonging to the Solar System that it will be worth while to consider what motions may properly be called real, before we try to understand how the planets really move.

112. We have seen already, in considering the Sun's rotation, that there is a sense in which no motion can be known to be real, because there is nothing in the universe which we know to be fixed. But even if we had something fixed to reckon from, the actual motions of other objects might not be called their real motions. We cannot imagine any possible way in which we could be assured that any celestial object was fixed, so as not to move at all; but let us suppose that we have been made certain of the fixity of some object like the Earth in every thing except its movements, and that we have been placed upon this fixed object. Let us now take a pail of water, and a piece of wood weighted with enough lead to make it sink in water, but not enough to make it sink fast. If the pail is not moved, and the sinker is put into the water, it will have an actual movement downwards, and this movement would be called a real one. But suppose that while it is going on the pail is lifted more quickly than the sinker goes down. Then the sinker would really be moving upwards, and yet no one would be likely to say that its downward movement was not just as real as ever. It is plain, then, that when we call a movement real, we do not always

mean that it really happens. In the case we have supposed, the sinker has two real motions, one downward, and a quicker one upward ; but nothing can really move two ways at once.

113. Suppose, next, that we were not aware at first of the lifting of the pail, and only found it out after a while. As long as we did not know of it, we should think that the downward movement of the sinker was the only movement it had. Now, when we learned that its actual movement was upward, we should not consider ourselves mistaken in thinking that it moved downwards. We should be as sure that it had a real downward movement as we were before, and should merely say that, besides this, it had an upward movement which was quicker than the downward movement already known.

114. It seems, then, that we do not always have to make an entire change in our notions with regard to the movement of a body when we learn something new about its movement, or even when we have been supposing it to move one way and find out that it is really moving the contrary way. If it were not for this, we should scarcely be able to learn any thing at all about the movements we see ; for we should be always changing our minds about them. But as it is, we do not need to have a fixed place, like that we have just supposed ourselves to have, before we can begin to study the movements of things around us. When we learn something new about the movement of any thing, we can often understand it best by keeping our old notions about the movement, and supposing the moving object to have another movement besides that which we had learned before ; so that we consider it as moving two ways, or perhaps many ways, all at the same time. On this supposition we can tell where its movement will bring it at any time just as well as we could by supposing it to have only one movement. So, too, we can suppose that any movement which we already know about is made up of as many different movements as we please. If a ship is sailing northwards ten miles an hour, we may say, if we please, that the ship sails northwards

fifteen miles an hour and southwards five miles an hour; and on this supposition we can tell correctly how much farther north than at present the ship will be half an hour hence. In the same way, we might suppose a ball rolling eastwards to be rolling north, south, east, and west all at the same time; and there might be reasons for actually making this supposition; for instance, the ball might be rolled eastwards in the cabin of a steamer steering west, and driven towards the north by a wind, and towards the south by a current; and the ball, under these circumstances, might on the whole move towards the east. Again, when a ball is struck northwards and westwards at the same time, it will be likely to move north-west, if the blows are about equally hard. In this case, too, we consider it as having two movements at once; and if we choose, we can consider it as having other movements besides these: a southward and a north-eastward movement, for example; only then we must change our notions of the speed of its northward and westward movements.

115. Any movement is said to be resolved into others, when we consider it as made up, or, according to the usual expression, composed of these other movements. All the movements which compose any movement are considered real, even if none of them are really made, as often happens. When we learn any thing new about the movement of a material object, and still consider the composition of that movement to be what we thought it before, except that a new movement is added to the others, we continue, of course, to call all these movements real. But it may also happen that our new knowledge makes us change our minds with regard to the best manner of resolving the movement of the object we are observing. In this case, some of the movements which we formerly thought real may no longer be called real movements.

116. Still, astronomers have learned so much about the movements of the celestial objects, that they can now be tolerably sure of continuing to regard many of them as among those into which other movements must be resolved, no mat-

ter what may be learned hereafter about these other movements. No one can tell, for instance, what is the actual movement of the Moon; but men saw long ago that it would be convenient to consider a direct (42) motion round the Earth as one of the motions into which the Moon's unknown motion may be resolved. It took much more time and thought to show the convenience of considering a direct motion round the Sun as another of these motions; but this is now fully admitted. Whatever may be discovered hereafter about the movements of the Moon, we may be pretty sure that we shall still find it convenient to consider both its direct movement round the Earth and its direct movement round the Sun as among those motions into which its actual motion is to be resolved. Accordingly, these two direct movements are commonly said to be real.

117. Any motion, then, is real, which we have reason to believe to be one of those into which it will always be convenient to resolve some actual motion. But what makes it convenient to consider motions as resolved into certain others? This question is easily answered. One great object of studying any science is to learn rules by which we can tell what to expect under certain circumstances. These rules are often called laws of nature; but they do not control events outside of us, but only our expectations. We are constantly changing and simplifying these rules, so as to make it easier to use them; but by so doing we alter nothing in the world without us. The more we learn, the wider we are able to make our rules, so that a few of our new rules will tell us more than many of those we begin with. Sometimes we lay down a rule which is the best we can get at the time, but which we expect to give up sooner or later when we have learned more about the subject to which it applies. A rule of this kind is called an empirical law. It would be laying down an empirical law, for instance, to say that water runs down hill; and that is a useful rule until we learn that quicksilver and other liquids also run down hill, that loose solids do so too, that both liquids and solids drop to the

ground when they are left without support, and also that if water is put under quicksilver it will run up instead of down, so as to come to the top of the quicksilver. When we consider all these, and many other facts like them, we see that our first rule is not exactly correct, and that if we say that any thing will fall through a liquid or a gas of less density than its own, we shall have a better rule, which we shall not be so likely to have to give up. Rules which are likely to last, and which take in many cases, are called general laws. A general law, of course, may be replaced by another law still more general. Still, it may continue to be useful for some purposes; and so may some empirical laws. It is one of the objects of the study of logic to show why we should regard some laws as empirical, and therefore not much to be depended on, while we can regard others as general, and be confident that they will be found correct in all cases. We need not stop here to consider the reasons which warrant us in thinking some laws to be more trustworthy than others.

118. General laws cannot always be expressed as simply as empirical laws, so that they are often hard to understand. But when they are understood, they help us much better than empirical laws to know what to expect, although we often have to consider many general laws, or many different applications of one general law, before we can tell what will happen under particular circumstances. When we are considering a movement, for instance, we have to think what it ought to be according to each of a number of rules, and then we can tell what it will be according to all of them taken at once. It is now plain that we shall generally find it convenient to consider every movement as resolved into others, each of them made according to some rule; and we thus have an answer to the question which led us to consider what we mean by laws of nature (117), so far as any laws of nature relate to movements.

119. We often see a movement repeated many times; and whenever this happens, we take it for granted that there must be a rule, or law, for that movement. We feel still more fully

convinced that it has a law, when it takes up very nearly the same length of time at each repetition. The swinging of a pendulum is a movement of this kind; so is the rotation of the Sun, or of the Earth; and all such movements are called periodic movements. The length of time required for each repetition of a periodic movement is called the period of the movement. All kinds of changes may be periodic whether they are movements or not; variable stars, for instance, may change their brightness periodically. When a movement does not seem to be periodic, we suppose, of course, that it goes on according to some laws of nature; but we usually presume that there must be many laws, or many applications of one law, to be considered before the movement can be explained. A periodic movement, on the other hand, is likely to go on according to a small number of rules; and even if we can find no general laws for it, we shall expect it to go on hereafter as it has been going on while we have been observing it. Now this expectation, whenever we express it, is itself the empirical law of the periodic movement we are studying.

120. A uniform movement is one which always goes on at the same speed. The simplest kind of movement which we can well think of is uniform movement straight onward. This is not commonly called a periodic movement, because its period may be considered to be just as long or just as short as we please. But if an object moves straight on, beginning to move at the rate of 10 miles an hour, gradually quickening its speed to 20 miles an hour, and then slackening it to 10 miles an hour again, we shall call its movement periodic, if it goes through similar changes of speed during every 50 miles of its course. In this example we may put any figures we please instead of the 10, 20, and 50, used above.

121. Some movements are considered to be both periodic and uniform. If an object moves ten feet north-west, then ten feet north-east, then ten feet north-west again, and so on in a zigzag line, always at the same speed, it has a uniform movement, divided into parts like each other, each part being made

in a given period. So, too, if any thing travels round and round in a ring, always at the same speed, its movement is both periodic and uniform.

122. When we wish to understand any movement which seems to be complicated, we generally begin by trying to resolve it into a set of periodic movements, and, if possible, of uniform periodic movements, each explained by general laws, or at least expressed by an empirical law. The science of astronomy began with attempts to resolve the observed movements of the Sun, Moon, and planets into uniform periodic movements. In this way certain empirical laws were formed; but as empirical laws never satisfy us very well, the early philosophers also made guesses about the general laws which account for the movements of celestial objects; and as men still had much to learn by observation before any such general laws could be drawn up, their guesses were often absurd. So are many of the guesses which people make in our own times, when they try to settle questions by general laws before enough has been observed to make it possible to draw up any laws but empirical ones. We are not so much wiser than the early astronomers were that we can afford to find much fault with them for their mistakes (17).

123. However, we are now able to explain many of the movements of celestial objects by certain general laws, known as the laws of motion. These laws can hardly be understood distinctly or used with success by any persons not thoroughly acquainted with mathematics. For the present we will content ourselves with an account of those motions of the Earth and similar objects which are considered to be real motions, in the sense above given to that phrase (117). Every real movement of the Earth answers to some movement of other bodies called an apparent movement. Apparent movements, in astronomy, are those which we should suppose various celestial bodies to have if we did not believe the Earth to have certain movements of its own. To illustrate this, we will consider how it came to be believed that the Earth turns daily upon an axis.

**124.** Nearly every one who lives either in the torrid zone of the Earth, or in one of its temperate zones, begins his acquaintance with astronomy by learning that the Sun rises every day on one side of any particular hill or building, and sets on the other; the side on which it rises being called the eastern, that on which it sets the western side. It is difficult not to learn as much of astronomy as this; but some people, perhaps, stop here, and never exactly know, when they see the Moon in the west soon after sunset, whether it rose there or not. But it takes very little observation to show that not only the Moon, but every star near which it ever seems to be, rises in the east and sets in the west, like the Sun; and also that, on the whole, these stars set about as long after they have risen as the Sun sets after it rises. This is not true of many of the other stars, however; for if we are anywhere in the north temperate zone, for instance, and look northwards on any clear night, we shall see many stars which never rise or set, and some which hardly seem to change their places in the sky at all. One of these is the star of the second magnitude (81) called the North Star, and also Polaris (38). The bright stars apparently near it seem to move round it in rings, going over it from east to west and under it from west to east; but even if we watch all night we shall not see any star go entirely round the North Star, because that requires about as much time as there is between one sunset and the next, so that the stars travel over part of their courses by day, when they cannot usually be seen. By observing stars which seem farther from the North Star than those we have just mentioned, we shall soon learn that they also go round it once in a whole day, but that the rings they move in are so large that they are partly out of sight, behind the part of the Earth which lies north of us. Suppose we see that one of the stars which seem only a little farther from the North Star than the North Star is from the horizon is setting early in the evening. If it moves in a ring while it is out of sight, it ought to rise before morning as far east of north as it sets west of north; and so in fact it will. By

comparing its movements with those of other stars seemingly somewhat farther from the North Star, we can make out that these other stars also move in ring-shaped courses, each star travelling over its whole course in about a whole day; and by continuing these observations, we can show that this is true of all the stars. We can also make out that a straight line drawn from some place in that part of the sky where we see the North Star to the place where we are, and beyond that, through the Earth, would pass through the middle of every one of the rings which form the daily courses of the stars. We shall conclude, then, that all the stars have a daily retrograde motion round the Earth, or, to speak more exactly, round the line we have just described. The motion is retrograde, because when we are facing north it is from right to left above and from left to right below; and when we are facing south it is from left to right above. This retrograde movement can be perceived most easily at places far from the equator; but observations which will show that it takes place may be made anywhere on the Earth without much difficulty.

125. The conclusion we have reached is an empirical law, and a true one; that is, it helps us to tell beforehand, without making any great mistake, what we are to see in the sky at particular times. Accordingly, this law is still in common use, among astronomers as well as among other people. For some purposes it is convenient to regard the Sun as having a daily retrograde movement round the Earth, and to consider this as one of the movements into which the actual motion of the Sun, whatever it may be, is to be resolved. If men had been content with statements like this, until they had collected observations enough of the facts of nature to enable them to lay down correct general laws about the daily movements of the stars, their astronomical knowledge would have been sound as far as it went. They need not have kept themselves from guessing at these general laws; for it is usually necessary to try a number of guesses before any general law can be found. But then the guesses ought to be of a kind that can be tried by observation; if we guess to save

ourselves the trouble of observing, instead of to give ourselves some particular thing to observe, we shall make no progress in knowledge.

126. One guess actually made at the general law of the daily periodic movement of the stars was as follows: that the stars were fixed in a sort of shell which enclosed the Earth, and that this shell turned round, carrying the stars with it, although it could not be seen, because it was transparent. Now if this law were true, it would still apply to few other movements besides those of the stars, so that it would be of little more service than the empirical law instead of which it was meant to be used. Besides this fault, the guess had another, that it did little to help on the observation of natural facts, and mainly served to make people think they knew something more than they did. It was taken by many men for a piece of knowledge, instead of a guess; so that, so far as it had any effect on the study of astronomy, it rather hindered than helped it.

127. Another ancient explanation of the daily movements of the celestial objects was that which we now consider to be correct. This explanation is that the Earth has a direct movement of rotation about an axis, and that one whole day is the period of this movement. This periodic movement is only one of those into which we resolve so much of the actual motion of the Earth as we have yet discovered; and it is to be regarded as a real movement in the sense above given to that phrase, but not as a movement actually performed, for two reasons. First, we do not know, and probably never shall know, what the actual motion of the Earth is; and secondly, if we suppose that we have already discovered the whole of this actual motion, then the actual course of any part of the Earth is not round and round, but onward in a peculiar winding curve; so that if we could have a clear notion of this movement given us, we should scarcely think it a periodic movement, or a movement made according to any laws simple enough to be found out. On the other hand, if we could be made certain that each part of the Earth al-

ways fronts the same way, so to speak, our belief in the Earth's real movement of rotation would not be altered, unless our present laws of motion were given up. We should simply have to suppose the whole universe, including the Earth, to have a daily retrograde rotation, just quick enough to counteract the direct rotation of the Earth. But, so far as we know, we cannot be made certain of any thing about the movements of objects, except that we can learn how they move with respect to each other. We may be sure, for instance, that two objects are coming nearer to each other, or going farther apart; but if they are coming together, we cannot tell whether this is because each is moving towards the other, or because one is stationary and the other moving towards it, or because both are moving the same way, but one faster than the other. We may resolve their movement towards each other into movements of as many kinds as we please, and we may suppose either of them stationary, whenever we find it convenient; but the use of all this is not to decide how the two objects actually move, but to help us to know how far apart they will be at any time hereafter. That is, we want to know what to expect; and for this purpose we resolve movements into others, and draw up the simplest and most general rules or laws of nature which we can invent. If any one could make a set of laws of motion by which we could foretell, more correctly and more easily than by the laws of motion now accepted, the results of the various movements going on upon the Earth and in other parts of the universe, these new laws would take the place of the old ones. But it is useless for people to propose new explanations of the movements of the planets, or to find fault with the explanations now in use, unless they show us some new way of calculating the results of all movements, whether those of the planets or any others, and also show by examples enough that this new way is easier to use than the old one, and that its conclusions agree with the facts of nature. Now, if we can be sure of any thing in human affairs, we may be sure that laws of motion which have been tried for centuries and

found always serviceable cannot be set aside by new discoveries, although perhaps some law may be found by which several of them may be all stated at once. Accordingly, there is not the least reason to expect that the movements we now call real movements will not continue to be called so; and any one who fancies he has made some new discovery about them must satisfy us that he knows accurately what astronomers think about them now before we can pay the least attention to his theories.

128. When the rotation of the Earth was first proposed as an explanation of the daily movements of the stars, hardly any general laws of motion had been discovered. It was known, however, that small solid objects are more likely than large ones to move about with respect to each other and to the largest objects around them. Great rocks and hills do not move about over the Earth like the pebbles tossed up by the sea or the thistledown floating in the air. This, after all, is only an empirical law, and is not entirely accurate. So far as it is true, it follows from the general laws of motion now known. At first, this empirical law seemed to be against the supposition of the Earth's rotation, because the distance of the stars was not known, and it was thought that they might be small objects compared with the Earth. Still, the guess that the Earth rotates was better than the guess that the stars are fastened to a rotating transparent shell (or crystal sphere, as it was called), because it would naturally set people to observing the Earth and to trying to make out the distance of the stars; whereas there was little to be observed about an imaginary transparent object. But in fact, the astronomers who first guessed at the rotation of the Earth do not seem to have been diligent observers, compared with some other astronomers of their times. By degrees, astronomers learned to determine the distance of the Moon tolerably well, and it became obvious that the other celestial objects were farther off than the Moon. As knowledge of this kind increased, it became more and more reasonable to suppose that the Earth might be only a small object com-

pared with others in the universe; so that the law which had formerly seemed to be against the supposition that the Earth rotates came to be rather in favor of it than otherwise. Other facts were gradually discovered, all showing that it would be necessary to consider the Earth as a rotating body in order to explain the facts of movement among celestial objects in the same way in which terrestrial movements were explained. Finally, but not till long after the opinion that the Earth rotates had been generally adopted, experiments were contrived which show that we must consider the Earth to rotate, or else give up the most general laws of motion yet discovered. One of these experiments consists in watching the swinging of a weight hung up by a cord or wire; but although this seems very easily done, the experiment needs much care to make it succeed, for the following reason.

129. If a weight is hung up and left until it seems to remain perfectly still, and then drawn to one side and let go, it will probably not swing back exactly to the place from which it was moved, which we will call its place of rest, but will pass a little to one side of it or to the other. After swinging some distance beyond this place the weight will of course swing back again, passing its place of rest on the side opposite that on which it went in its forward swing. It will continue to swing round this place, instead of through it, as long as it goes on swinging at all. Now, according to the laws of motion, it cannot do this and yet keep on following the same track with respect to the objects around it which it followed the first time it swung forward and back. Let us suppose that it was drawn towards the north from its place of rest, so that it began swinging nearly north and south; and let us also suppose that when it first swung southwards it went a little east of its place of rest. Then, when it is about to begin to swing northwards again, it will be a little farther west than it would have been if it had gone straight through its place of rest instead of going east of it. When it is about to swing southwards for the second time, it will be a little east of the place from which it set out the first

time. If we suppose it to have begun by passing to the west instead of to the east of its place of rest, it will shift its course the other way. On either of these suppositions, if it keeps on swinging long enough, it will after a time be swinging east and west instead of north and south; and if it was pushed to one side when it was first let go, so as to swing considerably west or east of its place of rest, the shifting of its course will be quick enough to be noticed every time it swings.

130. This experiment is easy to try, although it may sometimes be interfered with by disturbances in the air of the place or the framework of the building where it is tried, or by some resistance in the fastenings of the cord or wire which holds up the weight. But although it is in itself an interesting experiment, it gives us no distinct information about the rotation of the Earth. If, however, we can succeed in setting the weight in motion with so little disturbance that it goes at every swing straight through its place of rest, then also its course will shift, but more slowly than before, and in a way which depends on the part of the Earth where the experiment is tried. To understand the reason for this, let us first suppose that the experiment is tried at one of the Earth's poles. As the weight swings farther and farther away from the pole, it passes over ground which is moving more and more quickly by reason of the Earth's rotation. The weight, accordingly, falls a little behind the ground over which it moves, somewhat as a boat which has been rowed across a river to a place exactly opposite that from which it started is farther up stream than a floating log which was just in the line of its course when it set out. To complete the comparison, we must suppose the current to grow swifter as the boat goes on. When the weight swings back past the pole, it begins to pass over ground which is moving the other way from the ground over which it swung just before. This series of changes will be repeated every time the weight swings, and the course of the weight will therefore shift a little every time with respect to the ground beneath it. If the resistance of

the air and the stiffness of the apparatus did not give the weight some additional movement beyond that of swinging, its course would shift just as fast as the Earth rotated; so that at the end of one complete rotation of the Earth, the weight would be swinging just as it was at first; while at the end of half a rotation, the only difference would be that the forward swing of the weight would carry it over the ground the same way that its backward swing took it at first.

131. If the experiment is tried elsewhere than at one of the Earth's poles, the weight will not shift its course so quickly as in the case just supposed. At the equator, indeed, the Earth's rotation will have no effect on the motion of the weight, and the effect increases, according to known laws, with the latitude of the place where the experiment is tried, increasing, however, more rapidly while the latitude is small than when it is considerable. The effect is stated in mathematical language to be proportional to the sine of the latitude.

132. A heavy weight hung by a long wire is best adapted to the purpose of this experiment, which has sometimes been tried on a great scale in lofty buildings. However it is tried, the weight, when drawn aside at the beginning of the experiment, must be held back by a wire loop passed loosely round it, the loop being attached to some support by means of a combustible cord. When the weight has become entirely quiet in its new position, this cord is burned off by the flame of a match or candle held beneath it; the loop then drops off the weight, which begins swinging without any movement sideways, if the experiment has thus far been successfully performed. When it is tried on a small scale, pains must be taken to have the support firm, the weight smooth and round, and the air around it quiet. If the observer closes one eye and rests his head against some steady support, he can tell, by looking along the course of the weight at the string or wire on which it hangs, whether it is swinging straight or not. If it is, the string or wire will seem to keep the same

place, during the movement of the weight, upon whatever background may be beyond it; the flame of a steadily burning lamp, or a well lighted screen, with distinct marks upon it, will answer for this background. If any swaying movement can be seen, the experiment has failed. But after the weight has swung a few times without swaying, the observer, if he is in the northern hemisphere of the Earth, will have to shift his head slightly towards the left to keep his eye in the line of the movement. If he is in the southern hemisphere, he will have to move his head towards the right; the apparent shifting of the weight's course being everywhere retrograde, since the rotation of the Earth is a direct movement. Even when the experiment is carefully tried, the weight will probably soon begin to sway a little; but before this happens, it may have had time to show distinctly which way its course was shifting under the effect upon it of the Earth's rotation. The experiment will sometimes succeed with simple apparatus, such as a hollow india-rubber ball filled with shot and hung by a piece of floss silk some six or seven feet long, one end of it being carefully let into the ball, and the other, by means of a little plaster, into the ceiling.

133. The instrument called the gyroscope may also be used to illustrate the rotation of the Earth. It consists of a round flat piece of metal, with a heavy rim, set in such a frame that it can balance itself in any position. When it is made to spin round rapidly, it changes its position with respect to the objects around it in a manner which may be accounted for by the Earth's rotation.

134. Experiments of this kind show us the exact difference between real and apparent motion. When a swinging weight shifts the course along which it swings, the only fact we can observe is that the weight and the Earth have changed place in a certain way with respect to each other. What the actual movement of either has been we do not pretend to know; we cannot suppose that neither of them has moved, but we can suppose either of them to be stationary, and try to explain the movement of the other with respect to it by general rules

of some kind. The empirical law that small bodies move more than great ones would lead us to suppose the Earth stationary, and to resolve the observed movement entirely into movements made by the swinging weight. But the general laws of motion, which afford us by far the most convenient and exact methods of explaining the observed movement, require us to consider it as due to a real swinging movement of the weight and a real turning movement of the Earth; so that one of the movements which we are at first inclined to attribute to the weight is not to be regarded as real. In other words, the shifting of the course along which the weight swings is only an apparent movement, due to a change of place on the part of the observer, who is carried along with the Earth in its rotation.

135. In most cases of movement observed by astronomers, as in the instance just given, the laws of motion do not allow us constantly to consider any one of the observed objects as motionless. Still, we must have something fixed before we can determine the period of a periodic motion. We have already noticed this difficulty when we were considering the period of rotation of the Sun (43), and we are now ready to try to remove it. A meridian of the Sun, like a terrestrial meridian, is a line drawn round it as directly as may be, and passing through both poles. Now if we consider neither the Earth nor the Sun as having any other movement than that of rotation, then the period of the Sun's rotation will be that during which every meridian we choose to suppose drawn round the Sun has been twice turned edgewise towards any particular place in the Earth's axis. But, in fact, we consider the Earth and Sun as having other movements besides their rotation, and we can calculate their change of place with respect to each other, so far as it depends on these movements, from any one particular moment to any other. Supposing, then, these movements not to take place during one rotation of the Sun, we can calculate how much difference there is between the rotation of the Sun as it would be observed under such circumstances and as it is actually observed.

Taking this difference from the actually observed period of the Sun's rotation with respect to the Earth, we have the period which one rotation of the Sun is considered to occupy. Any new movements of the Earth and Sun which may be discovered, such as the exact movement of the Solar System in the universe, may cause us to alter what we call the period of the Sun's rotation; but, in fact, the only movements of importance in this inquiry are those by which the Earth is yearly carried round the Sun; more especially while the present uncertainty about the nature of the movements of solar spots with respect to each other continues. Any correction which may hereafter be made in the period assigned to the Sun's rotation will undoubtedly be very small, so far as it depends upon real motions of the Earth or Sun which are neglected by the astronomers of our times or unknown to them (46).

136. We have now considered the general meaning of the expressions which must be used in describing the movements of the planets. We must next settle on some meaning for the words north and south, direct and retrograde, when they are used with regard to bodies beyond the Earth, so as to avoid the necessity of a separate explanation for each body, such as that employed above in describing the Sun (38).

**137.** One of the real motions of the Earth carries it round the Sun once a year. Let us imagine a straight line drawn at some particular time through the exact middle of the axis of the Sun, directly towards the middle of the Earth's axis, and reaching both ways as far as we please from the Sun. The Earth, of course, will move away from this line at once; but we may consider the line as remaining fixed to the Sun's axis, and therefore as carried about with the Sun in all its movements except that of rotation. Now suppose a number of such lines drawn in the same way at different times. They will stretch out from the middle of the Sun's axis as the principal threads in a spider's web stretch out every way from the middle of the web; and we may suppose the spaces between them crossed by other straight lines, as the web is filled

up by cross threads. To distinguish between these two kinds of lines, we will call them principal lines and cross lines. The principal lines all cross each other at the middle of the Sun's axis, but nowhere else. Now let us suppose a number of cross lines joining any two of the principal lines and reaching both ways as far as we please beyond the lines which they join. We have now a sort of web of lines, containing, however, only two principal lines. All these lines might be touched at once along the whole length of each of them by any thing perfectly flat and sufficiently large. This is expressed in mathematical language by saying that all the lines lie in the same plane; what is meant by a plane being a perfectly flat partition or boundary, separating the universe into two distinct parts, but not itself taking up any room in either part. If we suppose a sheet of paper laid upon a perfectly flat table, and pressed so closely against it that the point of a pin stuck through the paper goes immediately from the paper into the table, this point nevertheless goes through the division, or, in other words, through the plane, which bounds the under side of the paper and the top of the table. If the table is tilted out of place, then this plane may be regarded as tilted along with it. A plane, then, may be said to rotate, or, in fact, to have any kind of movement which a material object can have; because it can always be regarded as bounding some flat material object, with which it moves about.

**138.** Let us now suppose the plane in which lie our two principal lines to have a movement of rotation about one of these principal lines as an axis. We will suppose that the other principal line takes no part in this movement, so that it is no longer in the plane as soon as the movement has begun. The cross lines, however, may be considered as belonging to the plane, and moving with it. Now, as a matter of fact, the plane will have made only a very small fraction of one complete rotation before any one whatever of the principal lines has been touched by some of the cross lines which we may suppose to have been drawn in the plane.

In other words, any principal line will be made to lie in the plane containing any two principal lines by a small movement of rotation of that plane. Still more simply, we may say that all the principal lines lie nearly in one plane.

**139.** The plane in which lie any two principal lines may be called the **plane of the ecliptic.** For our present purposes, it makes no difference which two principal lines we take to determine this plane, since the results will be much alike in all cases. The plane of the ecliptic cuts the Sun in halves, and, like all planes, separates the universe into two distinct parts; but these parts do not always remain the same, since the plane of the ecliptic is considered as fixed to the Sun's axis, and therefore carried about by the Sun, although not taking part in the Sun's rotation. The distance of the Earth from the nearest part of the plane of the ecliptic is never more than a small fraction of its distance from the Sun; this appears from the manner in which the plane of the ecliptic has been described. But it must be observed that the name "plane of the ecliptic" has various meanings in astronomy, although these meanings do not differ much from each other, and can easily be distinguished by the nature of the reasonings in which that name is used. The sense which has just been given to it is a convenient one for the purpose of describing the movements of the planets, and when we are acquainted with these movements, it will become easier to learn new methods of defining the plane of the ecliptic.

**140.** The Sun's axis is not itself a line lying in the plane of the ecliptic; therefore, since that plane passes through its middle, its northern half always lies on one side, called the northern side, and its other half on the southern side of the plane of the ecliptic. We have now the means of understanding what is meant by the direct movement of a planet round the Sun. Suppose that the planet could be watched from the middle of the Sun by an observer placed on the northern side of the plane of the ecliptic, and with his feet towards that plane. If the planet goes round the Sun in such a manner that it passes in front of this observer from right to left,

then its motion is direct, according to the account of direct motion already given. If it goes exactly over the observer's head and beneath his feet, its motion cannot be said to be either direct or retrograde, for it can never be said to pass in front of him from one side to the other. It may then be said to move in a plane perpendicular to the plane of the ecliptic, in which the Earth has been said to move round the Sun. It is very unlikely, of course, that any two bodies should be found to move in planes exactly perpendicular to each other; but if many of the bodies belonging to the Solar System moved in planes nearly perpendicular to the plane of the ecliptic, there would be little convenience in distinguishing between those of them which had direct and those which had retrograde motion. But in fact there are very few such bodies, and none of the principal planets ever go to any distance from the plane of the ecliptic which is considerable when compared with their distance from the Sun.

**141.** When any planet which has an axis of rotation is on the northern side of the plane of the ecliptic, its northern pole is the pole farthest from that plane; when it is on the southern side of the plane of the ecliptic the same northern pole is of course the nearer of the two to that plane.

**142.** Every known planet has a real direct movement round the Sun; every planet known to have any rotation upon an axis has direct rotation. Planets move round the Sun according to the laws of motion already mentioned. It follows from these laws that if we suppose lines drawn through the middle of the Sun's axis towards any planet at different times, we shall find, as in the case of the Earth, that these lines are nearly in one plane, if we suppose them all carried about with the Sun. We can then suppose the direction of all but two of these lines slightly altered, so as to make them all lie exactly in the same plane with those two lines, and call this plane the **plane of the planet's orbit.** We may next suppose a ring-shaped line drawn round the Sun in this plane, or, in other words, so as to cross every straight line of this plane which can be drawn through the middle of the Sun's axis. This ring-

shaped line must have some regular geometrical form, but must be drawn so that the planet may never be very far from the nearest part of it; it may then be called the **orbit** of the planet. Now the laws of motion will make it convenient to regard the movement of the planet round the Sun as resolved into a motion in an orbit and certain other motions. We may say, accordingly, that the planet has a real motion in its orbit, although its actual place may hardly ever exactly agree with any place in this orbit; so that a planet's orbit is not exactly the same as its course, or path, around the Sun; while neither its orbit nor its path round the Sun is the same as its actual course in space, of which we shall still be ignorant even after we have learned to attribute many real motions to the planets in addition to those we now attribute to them.

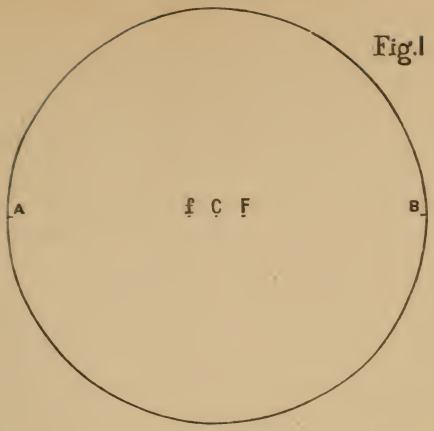
**143.** The plane of the Earth's orbit is the same with the plane of the ecliptic; but the Earth's orbit is not the same as the ecliptic. The explanation of the word ecliptic belongs to practical astronomy, and will be given hereafter.

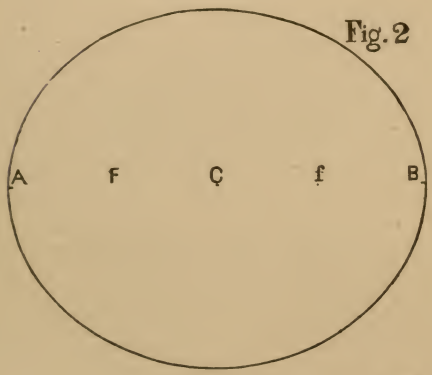
**144.** Since the orbit of any planet, and the plane of that orbit, are not visible objects, like the planet itself, but are only contrivances of our own, invented to help us to comprehend the planet's movements, it is not surprising that astronomers have found it convenient to consider orbits sometimes as lines having a fixed position with regard to the Sun, and at other times as shifting their places to some extent according to certain rules. This makes it difficult to define a planetary orbit or its plane in any way which will include all the meanings given to those expressions by astronomers, except by the aid of mathematical symbols; and the use of these symbols, although it guides our reasonings correctly, often keeps us from having a distinct understanding of the whole subject of those reasonings. But as the various meanings of a planetary orbit and its plane differ only slightly from each other, a statement of one of these meanings, such as that just given, will be enough to enable us to make ourselves acquainted with the general results of astronomical research.

**145.** The orbits of all known planets are **elliptical**. An **ellipse** may be drawn by fastening a thread to two pins stuck into a piece of pasteboard, for instance, and then moving a pencil over the pasteboard so as to keep the thread always stretched tight; that is, the pencil must move so that the whole distance to its point from one pin and from that point to the other pin always remains the same. If the thread is not much longer than the distance between the pins, the ellipse will be narrow in proportion to its length; and if instead of a thread we have a stiff wire stretched straight from one pin to the other, then the ellipse will be nothing but a straight line between the pins; or, in other words, its width will be nothing in proportion to its length. On the other hand, if the pins are very close together in proportion to the length of the thread, the ellipse will be nearly as wide as it is long; and if both ends of the thread are fastened to a single pin, there is no longer any distinction between width and length in the ellipse, which is then called a circle. The places of the pins in the pasteboard are called the **foci** of the ellipse. The **centre** of the ellipse is half-way from one focus to the other. The straight line from one end of the ellipse to the other, passing through both foci and the centre, is the **major axis** of the ellipse; half of it is the **semiaxis major**. The quotient obtained by dividing the distance between the centre and either focus by the semiaxis major is the **eccentricity** of the ellipse; that is, if each focus is half way from the centre to the end of the ellipse, the eccentricity is $\frac{1}{2}$. If the ellipse is nearly a circle, the eccentricity is nearly 0; for then the foci are close to the centre. If the ellipse is nearly a straight line, the eccentricity is nearly 1; for then it is almost as far from the centre to either focus as from the centre to either end of the ellipse. All this will be easily understood by any one who will take the trouble to draw several ellipses of different shapes.

**146.** In every planetary orbit the Sun is not in the centre, but at one focus of the ellipse. When the planet is at that end of the ellipse nearest to the Sun, it is at its **perihelion**;

# PLATE III.



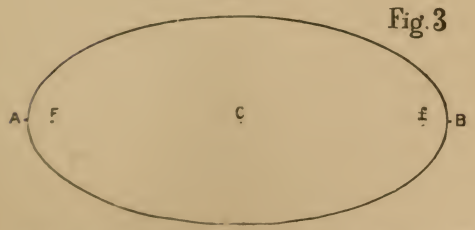




FIG. 1. Major axis 2 inches; $0\frac{1}{4}$ inches between foci; hence eccentricity $\frac{1}{8}$. This ellipse scarcely differs in appearance from a circle. The eccentricity of the Earth's orbit is less than $\frac{1}{7}$ of $\frac{1}{8}$.

FIG. 2. Major axis 2 inches; 1 inch between foci; hence eccentricity $\frac{1}{2}$. This ellipse is more eccentric than that of the orbit of any known planet.

FIG. 3. Major axis 2 inches; $1\frac{1}{2}$ inches between foci; hence eccentricity $\frac{3}{4}$. This ellipse is somewhat more eccentric than the orbit of Encke's comet.

when it is at the opposite end it is at its **aphelion.** The greatest eccentricity of any known planetary orbit is about $\frac{1}{3}$; that is, a planet having such an orbit is about twice as far from the Sun when it is at its aphelion as it is when it passes its perihelion. The orbits of the larger planets are less eccentric; the eccentricity of the Earth's orbit, for instance, is only about $\frac{17}{1000}$, so that the Earth's orbit is much like a circle.

**147.** Since the distance of a planet from the Sun is different in different parts of its orbit, this distance cannot be set down in figures which will always be correct. Accordingly, when the Earth, for instance, is said to be about one hundred and eight times as far from the Sun as the poles of the Sun are from each other, what is meant is that the semiaxis major of the Earth's orbit is about one hundred and eight times as long as the distance between the Sun's poles. The length of the semiaxis major of the orbit of any planet is what is called the **mean distance** of that planet from the Sun; and when a planet's distance from the Sun is mentioned, we understand that this mean distance is meant, unless we are expressly told that it is not.

**148.** Planets move faster in their orbits the nearer they are to the Sun; so that, of a number of planets, that which is nearest to the Sun moves quickest, and each moves faster at its perihelion than at its aphelion. A straight line drawn from that focus of a planetary orbit at which the Sun is situated to that part of the orbit in which the planet is situated is called the **radius vector** of the planet; and this radius vector may be supposed to be carried round with the planet, like an elastic string joining it to the Sun, and shortening or lengthening as the planet approaches the Sun or retires from it. On this supposition, the radius vector sweeps over the whole of the space surrounded by the orbit while the planet travels once over the whole circuit of the orbit; and while the planet travels over any given part of that circuit, the radius vector sweeps over a corresponding part of the space which the orbit encloses. Now the rate of any planet's motion along its orbit is such that the space swept over

by its radius vector in a given time is equally large in all parts of the orbit. This space will have different shapes in different parts of the orbit. Near the perihelion it will be comparatively short, measured from the Sun to the planet, and comparatively wide, measured along the orbit; near the aphelion it will be comparatively long and narrow; and in all cases it will of course run up to a point at that focus of the orbit where the Sun is situated. But it will always be equally extensive, or, to use a geometrical phrase, it will always have the same area. To make this clearer, let us suppose that the orbit of a planet runs along the edge of an elliptical metal plate of uniform thickness, so that a square foot of this plate taken from any part of it will weigh just as much as a square foot taken from any other part. Let us suppose a pin to be set in this plate at that focus of the ellipse which is in fact occupied by the Sun; and suppose an elastic string connecting the planet with this pin to represent the radius vector. Then the weight of that part of the plate touched by the string during ten days, for instance, while the planet is moving in one part of its orbit, will be the same as the weight of that part touched by the string during any other ten days, while the planet is moving in some other part of its orbit. That is, although these parts of the plate may be of different shapes, they contain equal quantities of metal.

**149.** If one planet is four times as far from the Sun as another, it will be eight times as long as that other planet in completing its circuit round the Sun; if it is nine times as far from the Sun, the time of its circuit will be twenty-seven times as great; if it is sixteen times as far from the Sun, the time of its circuit will be sixty-four times as great; and so on, according to the same rule. The general statement of this rule is that the squares of the periodic times of any two planets are to each other as the cubes of their mean distances; but the above instances of its application may perhaps give a better notion of its meaning than this general statement does. The distances of the planets are not related to each other in such simple proportions as those just used

for the sake of illustrating the rule, so that the fractions showing its actual use are too complicated to allow their relations to be easily seen.

**150.** The rules which have just been stated are generally known as **Kepler's laws**. Stated briefly, they are as follows: —

The orbit of every planet is an ellipse, at one focus of which the Sun is situated.

The radius vector of every planet traverses equal spaces in equal times.

The squares of the periodic times of any two planets are to each other as the cubes of their mean distances.

151. The progress of astronomy since the discovery of these laws has enabled us to show not only that they are special instances of the working of the general laws of motion, but also that they are not perfectly exact statements. However, what has been said about the true nature of real motions will make it seem likely, at least, that if Kepler's laws do not express the whole truth respecting the movements of the planets, they may still be considered accurately true when their language is fully understood. In fact, they still remain the best known summary of our knowledge upon the subject to which they relate; and there is accordingly no reason to suppose that they will go out of use in astronomical works.

152. The second and third of these laws are evidently in some way related to each other, on the supposition that any general rules for the velocity with which planets move can be laid down. For the second law determines the relative speed of a planet in different parts of its orbit, while the third determines the relative speed of different planets; and the result in both cases depends upon the distances from the Sun of the planets which are considered. But at first sight these two laws may seem inconsistent with each other. If we try to extend the application of Kepler's second law to the movements of separate planets, we shall expect to find the movement of a planet four times farther from the Sun than another

not eight but sixteen times as slow as that of this other planet. But the laws of motion must be separately applied to the case of each planet, when we wish to determine its movements. We cannot take it for granted that all planets move alike, although we may take it for granted that there is little change from time to time in the rules by which the movements of any one planet are to be calculated. Kepler's second law applies to many movements besides those of celestial objects. Let a small weight, for example, be whirled round a few times at the end of a string, and let the string be allowed to coil itself round the finger as the weight continues to revolve. The increase of speed in the movement of the weight as the string shortens will illustrate the same rule as that in accordance with which the Earth quickens its movement round the Sun as it approaches its perihelion.

**153.** The laws of motion, as now understood, will be explained to some extent in that part of this work which relates to theoretical astronomy. It will be enough for the present to state that the Earth or any other planet falls towards the Sun, according to the laws of motion, as a ball thrown into the air, or fired from a gun, falls towards the Earth. The impulse given to such a ball is counteracted by the resistance of the air, and at length fails any longer to keep the ball from coming to the ground. Even if there were no air to stop the ball, it might strike against the ground in some part of its course, and thus be prevented from circulating round the Earth, as the Moon does, and as the Earth itself circulates round the Sun. But if the ball were thrown forward horizontally with sufficient force, or if the Earth would open before it as it came to the ground and give it a free passage, it would go, in the absence of air or other impediments, not exactly towards, but past the middle of the Earth, round which it would continue to travel in an ellipse or a circle, unless its original speed had been too great. In that case it would move away from the Earth altogether in one of the curves known as parabolas or hyperbolas, its falling movement being enough to bend its course a little, but not enough to bring it back.

**154.** The mass of the Sun being more than 320,000 times that of the Earth (47), we say that the Earth falls towards, or rather falls past, the Sun, not the Sun towards or past the Earth; just as we say that a ball falls towards the Earth, not the Earth towards the ball. Still, in the strict application of the laws of motion to all facts of the kind we are now considering, we must speak of the movements performed by each of at least two bodies with respect to the other; for example, we must say not that the Earth falls towards the Sun, but that the Earth and the Sun fall towards each other, while their forward movements keep them from meeting anywhere, and these falling and advancing movements taken together make them circulate perpetually around each other. But the share of the Earth in this joint movement is far larger than that of the Sun, much as a horse, when employed to move a large building by means of a windlass, has to travel a great deal farther than he carries the building.

**155.** The Earth is not hindered in its forward movement by any thing capable of checking it as the air does a ball. The ether may possibly retard it a little, but is not known to do so. The meteors which are constantly striking the Earth may also check its course, but they have not yet produced any noticeable effect upon it. The laws of motion do not in themselves account for the fact that the Earth has a forward movement as well as a falling movement; they only show what will happen when this forward movement is once begun. There has been much speculation upon the origin of movements of this kind among the celestial bodies, but it is not worth while for any but accomplished astronomers to pay attention to so difficult a subject (17) as that of the origin of the present structure of the universe. Whatever knowledge of past ages we may obtain, it is at all events unlikely that we shall be able, by astronomical research, to show the matter now composing the material universe to have been at any time devoid of motion.

**156.** In giving an account of the peculiarities of the planets considered separately, it will be convenient to begin with the

Earth, because we know most about it. As we have seen, it has an **axis of rotation**, turning round on that axis once in about a day. That pole of the Earth nearest Greenland is called the **north pole**, and that nearest Australia the **south pole**. To travel north upon the Earth means to travel as directly as possible towards the north pole. To travel east or west means to move upon the Earth so as to keep always at the same distance from the north pole; if this movement is direct, it is towards the east; if retrograde, towards the west. East and west, then, are words with a very different kind of meaning from that which belongs to the words north and south. There is no place on the Earth east of all other places on it; but if we could travel, for example, to the south pole of the Earth, then we could not go any farther southwards, unless we could leave the Earth altogether and travel on along the line of its axis. If we went away at all from the south pole without leaving the Earth, we should be travelling northwards; at first starting, we could not even go north-east or north-west. But as soon as we had reached any distance from the south pole, however small that distance might be, we could travel east or west round the pole as long as we chose without ever being as far east or as far west as we could go. There are other ways in which the difference between the words north and south and the words east and west may be made to appear, but we need not examine them at present.

**157.** If we suppose the Earth's axis divided in the middle into a northern and a southern half, the place of this division is what we will call the **centre** of the Earth. Suppose a straight line drawn from any place on the Earth through its centre to the opposite side; then the two parts of this line on opposite sides of the Earth's centre will be nearly equal to each other. The height of the Earth's mountains is not great enough to make a noticeable difference in measurements of its thickness (1). Any straight line drawn from side to side of the Earth through its centre may be called a **diameter** of the Earth: either of the two equal parts of

a diameter which are on opposite sides of the centre may be called a **radius**; or, as is more usual in astronomy, a **semi-diameter**. Any globular body like the Earth in shape may be said to have a centre, and to have diameters and semi-diameters or radii, whether one of the diameters is an axis of rotation or not. The longest of the straight lines which can be drawn through such a body from one side to the other will be one of the diameters, and the centre will of course be half-way from one end of this diameter to the other.

**158.** An **equatorial diameter** of the Earth is a diameter with its ends in the Earth's equator; there may be as many equatorial diameters as we choose to suppose. The **polar diameter** is that which reaches from pole to pole, or, in other words, it is the axis, unless we make no distinction between the axis itself and the **line of the axis**, which may be supposed to reach out as far as we please from the Earth. There can be only one polar diameter, as appears from the meaning of that expression. If any diameter of a globular body is considered as an axis, it may be called the polar diameter of the body, and its ends may be called poles. The line drawn round the body half-way between these poles may then be called an equator, and diameters ending in the equator will be equatorial diameters.

**159.** If every diameter of a globular body is exactly as long as any other diameter of the same body, the shape of that body is spherical, and the body itself may be called a sphere. The Sun, for example, or that part of it within the chromosphere, is spherical in form, so far as is known; but its disk cannot be measured very accurately (76). The Earth cannot be considered spherical, even if we disregard the irregularities of its shape occasioned by its mountains and hollows. It has the shape of what is called in geometry an **oblate spheroid**. This means that its polar diameter is the shortest of all its diameters, and that its equatorial diameters are the longest. If we suppose it cut into its northern and southern hemispheres, the shape of the section thus made through it will be nearly circular; but if it is cut into

any other pair of hemispheres, the shape of the section will be elliptical; and the ellipse will be most eccentric when the section is made along the axis. Even then, however, the ellipse will be much like a circle, since the polar diameter of the Earth is less than thirty miles shorter than an equatorial diameter. Certain measurements have been thought to show that the equatorial diameters of the Earth differ in length to some extent.

**160.** According to the laws of motion, every thing on or near the Earth must seem heavier the closer it is to the Earth's centre. We have just seen that the poles are nearer to this centre than other places on the Earth are, and that the ends of equatorial diameters are farthest from it. Accordingly, the weight of every terrestrial object must seem to increase as it is carried from the equator towards either pole. But this cannot be shown with an ordinary pair of scales; for whatever we put into one scale will grow heavier just as fast as what is put into the other scale. The rate at which a pendulum swings, however, depends on the length and also on the weight of the pendulum; not its weight compared with that of another pendulum of the same length, but the speed with which it would drop to the Earth if allowed to fall. It has been found, accordingly, that a pendulum which swings once every second when it is near the Earth's equator will swing a little more than once every second in other parts of the Earth. Although a pendulum would not swing much faster even at one of the poles than at the equator, there is still difference enough between the rates at which a pendulum swings in two places like New York and Panama, for instance, to be discovered by counting the number of times the pendulum swings in a few hours at each place. The experiment has been tried in many places and at different times, with all proper precautions to prevent changes of temperature and atmospheric resistance from affecting the result. It has thus been found that the difference in the rate of a pendulum in different parts of the Earth is too great to be accounted for only by the shape of the Earth, as deter-

mined by what is called surveying. We must look, then, for some additional reason why bodies on the Earth should grow lighter as they are carried towards the equator. This reason is the Earth's rotation on its axis, which daily carries a body placed at the equator as far as it is round the Earth, or nearly 25,000 miles, while a body near either of the poles is moved by the Earth's rotation only a short distance in the same time. When a carriage is driven fast over wet ground, the wheels take up mud and fling much of it off again every time they go round. This, of course, is because the lower part of each wheel is carried backward by its rotation, so that it is not moving forward as fast as the body of the carriage. The top of the wheel, on the contrary, is moving forward faster than the body of the carriage. As the forward movement of any part of the wheel's rim grows quicker while that part of the rim is rising from the ground, some of the mud which stuck to it while it was moving forward more slowly is thrown off, a part at a time; and all of it may be thrown off if the carriage moves fast enough. We can imagine the Earth to rotate so rapidly that any thing brought near its equator would in like manner be flung off, although objects might still rest upon it near the poles. In this case, nothing at the equator could be said to have any weight. We actually find that any object — a pendulum, for example — clings less firmly to the Earth the nearer we bring it to the equator, on account of the Earth's rotation as well as on account of its shape. We must remember, however, that there is a difference between the reasons why mud sticks to a wheel and why movable terrestrial objects remain upon the Earth. The explanation of this difference belongs to mechanics rather than to astronomy, and does not affect the fact that material objects which cling together in either way mentioned above may be separated by a particular sort of motion.

**161.** It may be asked why the Earth's motion in its orbit does not lessen the weight of terrestrial objects as its rotation does. In the illustration just given, it is the forward motion of the wheel, as well as its rotation, which throws off the

mud. But both these movements make a difference in the speed of the rim of the wheel with respect to the Earth. Now the Earth's rotation likewise makes a difference in the speed of different parts of the Earth with respect to each other; but the Earth's movement in its orbit has no such effect.

**162.** A pendulum, as we have now seen, may be used in two different ways to show that the general laws of motion require us to attribute a real movement of rotation to the Earth. The first way is to set it swinging so that it may shift the line along which it swings with respect to surrounding terrestrial objects; the second way is to count the vibrations it makes in a given time in different places. In this second method, however, the Earth's rotation is not shown to be direct, and the shape of the Earth has to be taken into account. But this shape itself, or rather the shape of the water forming the ocean, requires us, if it is to be explained in accordance with the laws of motion, to assume that the Earth rotates. The ocean extends at the equator more than twenty-six miles farther from the Earth's centre than it does near the poles. But water always settles into hollow places upon the Earth when it can; that is, it flows towards the Earth's centre whenever matter heavier than itself does not keep it from doing so. The water near the equator, then, must be lighter, in a certain sense, than the water near the poles, or it would flow towards the poles and distribute itself over the polar regions of the Earth in such a way that the ocean, wherever it was situated, would extend equally far in all its parts from the Earth's centre. If a fluid sphere is made to rotate upon an axis, it takes the shape of an oblate spheroid, and finally, if the rotation is quick enough, it is changed into a ring. This experiment has been tried with a small quantity of oil placed in a mixture of alcohol and water just as dense as the oil itself. Under these circumstances the oil takes the form of a sphere, which may be made to rotate by piercing it with a wire and gently turning the wire. The equatorial portions of the sphere, or those which are already

farthest from the wire, are then carried out still farther ; along the wire, on the other hand, the sphere contracts. If the Earth, according to the ordinary belief, was formerly altogether liquid or gaseous, we can readily account for its present form by the fact of its rotation. But it is now partly composed of water, and this water is constantly wearing away and building up the land, so as to distribute it in new ways. Hence the Earth would even now be likely to work itself gradually into its actual form, if it had not already been moulded into that form ; and volcanic action, or whatever else may tend slightly to alter its present shape, is counteracted by the waves and currents of the ocean.

163. The trade-winds, as they are called, and in fact all the various currents of air and water which are observed upon the Earth, depend to a great extent upon the fact of the Earth's rotation ; but their description belongs rather to the study of physical geography than to that of astronomy.

164. What has been said above of the difference in weight of bodies placed in different parts of the Earth may be difficult to understand, unless some notice is taken of the vague meaning which the word weight commonly has. For this reason, the word mass (10) is always used in speaking accurately of what is sometimes understood by weight. Any particular piece of iron has the same mass in one place on the Earth that it has in another ; but, owing to the Earth's rotation and shape, it clings less firmly to the Earth, or, in one sense, has less weight, the nearer it is brought to the equator.

165. The Earth has other real motions besides those already considered. In speaking of its rotation alone, we regard its axis as motionless ; but we find that its various parts move with respect to each other in other ways than those which are described by saying that it rotates on its axis. To understand these movements, we must regard the Earth's centre only as fixed, and suppose it to swing round this centre so that its axis may be made to point to different parts of the universe at different times, always passing, however, through

the same parts of the Earth. To see what this motion is, we need something which we can consider fixed for the time of our inquiry, and with which the position of the Earth's axis can be compared. We can accomplish this in the following way.

166. Let us suppose the Earth's centre to be situated in the plane of the ecliptic, as it will sometimes be, however we define that plane. Then, as a matter of fact, the hemisphere of the Earth lying on the northern side of the plane of the ecliptic will not be exactly the same as what we call its northern hemisphere, when we consider it as divided at the equator. Its north pole, indeed, will be on the northern side of the plane of the ecliptic, and its south pole on the southern side of that plane. But half of its equator will be on the northern side, and half on the southern side of the plane of the ecliptic. Hence one of its equatorial diameters will lie in the plane of the ecliptic, its ends marking the places where the equator passes through that plane. If the Earth should turn about this diameter as an axis, its equator might be made to lie in the plane of the ecliptic, so that the whole of its northern hemisphere should lie on the northern side of the plane of the ecliptic. To accomplish this, it would have to turn through about $\frac{1}{115}$ of a complete rotation. The Earth has a real motion of this kind; but it is slow, and its amount never becomes large enough to be perceptible, except by delicate observations; for it is reversed at regular intervals; that is, the Earth tilts so as to carry its equator alternately a little towards and a little from the plane of the ecliptic. This real motion of the Earth may be called its nutation in latitude. But another circumstance occasions a greater effect of the same kind. We have seen that however we define the plane of the ecliptic, we shall not always find the Earth's centre in that plane. That is, if we determine the plane of the ecliptic at different times by our former method (139), we shall obtain a number of planes, differing from each other perceptibly, though not greatly. Now astronomers have found it convenient, under these circumstances, to consider

the plane of the ecliptic as gradually passing, according to certain rules, from one position to another. Accordingly, what they call the plane of the ecliptic depends upon the time of the events which they are considering. Changes of this kind must keep the Earth's equator and the plane of the ecliptic, as well at times when the Earth's centre is in that plane as at other times, from always sloping towards each other in exactly the same way. But the motion of the plane of the ecliptic is very slow, and, like nutation in latitude, it is reversed in the course of time; and consequently the amount by which the Earth must turn to bring its northern hemisphere wholly to the northern side of the plane of the ecliptic (when its centre is in that plane) never differs much from $\frac{1}{115}$ of a whole rotation. The usual statement of this fact is that the obliquity of the ecliptic is about $23\frac{1}{2}$ degrees. Exactly $\frac{1}{115}$ of a whole rotation is 24 degrees, so that $\frac{1}{115}$ of a whole rotation would be more than enough to bring the whole of the northern hemisphere to the northern side of the plane of the ecliptic in the manner just described; but as the amount of rotation which would be required is constantly changing, no figures will express it exactly, except for some particular moment of time. By its nutation in latitude the Earth tilts once back and forward in less than twenty years; the tilting of the plane of the ecliptic occupies thousands of years at a time; but although it goes on so long without reversal, and is in fact a much larger movement than nutation in latitude, it is so small that careful observations are needed to detect its results. It may be surprising to find that one of the movements called real is a movement of an imaginary thing, known as the plane of the ecliptic; but of course the moving body is in fact the Earth, according to the explanations already given.

167. We now come to more obvious real movements of the Earth, known as precession and nutation in longitude. In studying geography, we learn the places of certain circles which are considered as the boundaries of the temperate zones, and called the Tropics and the Arctic and Antarctic

Circles. These boundaries are not absolutely fixed, but must be considered as changing their places according to the changes which we consider as taking place in the plane of the ecliptic ; so that wherever the Earth is, either the Arctic or Antarctic Circle must pass through that place on the Earth which is farthest from the plane of the ecliptic. If the Earth is on the southern side of that plane, it will be the Antarctic Circle which passes through this farthest place ; if on the northern side, it will be the Arctic Circle. If the Earth's centre is in the plane of the ecliptic, there will be two places on it farther from that plane than any others, the Arctic Circle passing through one and the Antarctic Circle through the other. In order to have a name for these places, let us call them the terrestrial poles of the ecliptic. Wherever the Earth is, one of them at least is as far from the plane of the ecliptic as any terrestrial place that can be found ; and the other is directly opposite to it. The rotation of the Earth on its axis prevents these terrestrial poles of the ecliptic from remaining any length of time, however short, at any particular parts of the Arctic and Antarctic Circles. Still, at any moment, the Earth is to be regarded as having a retrograde rotation, so slow that it is repeated less than four times in a hundred thousand years, about an axis which we may call the same as the line drawn from one terrestrial pole of the ecliptic to the other. The general name of precession is applied to the visible effects produced by this slow rotation, which may itself be called the precessional movement of the Earth. Considerable changes are always going on in the precessional movement of any part of the Earth at a distance from its ordinary axis of rotation, since the axis of the precessional movement is constantly shifting. Nutation in longitude is a smaller movement, by which precession is at one time increased and at another diminished. Precession, nutation in longitude, and nutation in latitude (166), may all be considered parts of a single movement ; but it is often convenient to regard that movement as resolved into others, in the way just described.

168. In consequence of precession, the appearance of the sky, as seen from any particular part of the Earth, is always changing; although the change is so slow that it may go on for a century at a time without being noticed by any one who does not make careful observations of the stars. In a thousand years, however, the change would become great enough to be very obvious to people who could remember the beginning and witness the end of such a period. About four thousand years ago, an observer stationed at the north pole of the Earth would have had a certain star ($\alpha$ Draconis) in the constellation Draco, instead of our present North Star, nearly over his head; while twelve thousand years hence, the line of the Earth's axis will point nearly enough to Vega to allow that to be considered the North Star in its turn. It is well to notice that this change is not due to any shifting of the place of the Earth's axis in the Earth, but to a movement of the Earth itself about its centre, as has been said already (165). This movement, of course, does not change the situation of one star with respect to another, as seen from the Earth, but only alters our view of the whole visible universe at once.

169. Astronomers not only consider the plane of the ecliptic as variable, but regard the Earth's orbit as changing in that plane. The most important change of this kind is a direct movement of the whole orbit round the Sun. This movement, called the revolution of the apsides, is very slow.

170. We have now considered all the more important movements of the Earth. The small movements by which it may be considered as carried a little out of its orbit, or even out of the plane of the ecliptic, in spite of the supposed movements of that orbit and plane, are called perturbations, and depend on the places of the other bodies of the Solar System at particular times.

171. The movements of the Earth about its centre may be illustrated in the following manner. Take a ball of any convenient size, and draw a line round the middle of it to represent the Earth's equator. Make two dots on the ball as far

as possible from this equator for the poles, and mark one of these poles as the north pole. Stick a pin into the ball at this north pole, so that when the north pole is at the very top of the ball the pin may stand upright. Take a box partly full of sand, level the top of the sand, and place the ball in it so that half of the ball may be below the top of the sand and half above, with the north pole in the half above the sand, but not at the very top of the ball. We may consider the level of the top of the sand as representing the plane of the ecliptic, its upper side being regarded as its northern one. If it would take about $\frac{1}{15}$ of a rotation of the ball, round an axis drawn between the places where its equator dips below the sand, to bring its whole equator to the level of the sand, and its north pole to its very top, then the ball stands with regard to the level of the sand about as the Earth does with regard to the plane of the ecliptic. Put a cover partly over the box, so that the pin which marks the line of the axis may point towards some place in this cover, and mark that place. Turn the ball round and round without moving it about in the sand, so as to keep the pin always pointing towards the marked place, and so that every part of the equator which is above the sand may move from the left to the right of a spectator who faces it. If the spectator faces the north pole instead of the equator, the top of the ball will move from his right to his left. This will accordingly be direct rotation, and will represent the daily rotation of the Earth. Next, turn the ball so as to keep the north pole always just at the same height above the sand, and so that it may go round from the right to the left of a spectator facing it, but still without changing the place of the ball in the sand. If the spectator looks directly downward on the sand, he will see that this movement is retrograde. This twisting movement will represent precession and nutation in longitude. Nutation in latitude may be imitated by rocking the ball in the sand, so that every part of its equator above the sand may remain above it and every part below it may remain below. If the same movement of the ball with regard to the sand is effected

by holding the ball still and tilting the box of sand, the motion imitated is that of the change of the obliquity of the ecliptic; but, as we have seen, a change in the obliquity of the ecliptic means only that no plane will answer permanently for the plane of the ecliptic. It may be convenient, instead of using sand, to place the ball on a table, over which a sheet of paper has been stretched at such a height that when the ball is set in a round hole cut for it in the paper, half of it will be above the paper, and half between the paper and the table. We must remember that these movements, which we imitate one by one, are only movements into which we find it convenient to resolve a part of the Earth's motion.

172. The movements of the Earth except those about its own axis and centre cannot readily be imitated for want of room enough to imitate them on the proper scale. If we have a ball one inch only in diameter to represent the Earth, we need a ring over one-third of a mile across to represent its orbit. On the same scale, the Sun would be a ball nine feet through, and the Moon a little ball about a quarter of an inch in thickness, placed about two and a half feet from the ball representing the Earth. Hence all ordinary attempts to represent the movements of the planets tend to confuse the learner about as much as to help him.

173. We need not here pay much attention to the structure of the Earth, with its oceans and atmosphere, for such topics belong to geology and to physical geography. But in order to compare the Earth with other planets we may notice a few of the prevalent opinions respecting it. We know scarcely any thing either of its interior or of the outer portions of the air which surrounds it. It is generally believed that its heat increases towards its centre; and it has been thought that its inner portions may be so hot as to be liquid. This, however, is far from being proved; and at present the opinion seems to be gaining ground that the Earth's interior is largely if not mainly in a solid state. On this theory, the facts of volcanic action are explained by the heat caused

by the rubbing together and by the crushing of portions of the outer parts of the Earth. These effects, again, are supposed to be caused by the gradual cooling and shrinking which is thought to go on in the Earth. In this way the outside roughnesses of the Earth, its mountain chains and the hollows filled by its oceans, may be accounted for as well as on any other supposition. But the reasons for all these opinions cannot be understood by any but thorough students of mathematics and the physical sciences.

174. As to the Earth's atmosphere, we know that its density becomes rapidly less as it extends farther from the land and sea; so that the mass of all the air more than ten miles from the land and sea is probably trifling compared with the mass of the remainder. But it is still doubtful where the Earth's atmosphere ends; and certain facts noticed with regard to Northern Lights and shooting stars have made it seem likely that this atmosphere reaches several hundred miles from the solid Earth. Some astronomers think that it has an actual limit somewhere, while others think it has none. On this view, the air is only that portion of the gaseous matter existing throughout the universe which the Earth may be carrying about with it at any particular time. The gases existing in its outer regions may perhaps differ from those which have hitherto become known to chemists.

**175.** The Earth, then, is an oblate spheroid (159) of solid and liquid matter, surrounded by a gaseous atmosphere of unknown extent and form, which contains much floating solid and liquid matter; rotating on its shortest diameter as an axis once in every period called a day; revolving about the Sun once in every period called a year, its path in this revolution being nearly in a plane, called the plane of the ecliptic, to which its equator is inclined about $23\frac{1}{2}$ degrees, and nearly in the shape of an ellipse of very little eccentricity; having a peculiar twisting movement which may be resolved into one of precession, accomplished in over 250 centuries, and one of nutation in longitude and latitude, completed in less than 20 years; at a mean distance (147)

of about 108 diameters of the Sun from the centre of that body; and known to be attended by one satellite, called the Moon. It will be convenient to describe this satellite before going on to speak of the remaining planets. In describing it, we must begin with an account of its movements, upon which our acquaintance with its other peculiarities partly depends.

**176.** First, then, the Moon has direct rotation upon an axis so situated that its equator is inclined only about $1\frac{1}{2}$ degrees to the plane of the ecliptic. In other words, when one of the Moon's equatorial diameters lies in the plane of the ecliptic, which must happen whenever the Moon's centre comes into that plane (166), about $\frac{1}{240}$ of a whole rotation of the Moon about that diameter as an axis would be enough to bring its whole equator into the plane of the ecliptic. Next, the Moon revolves about the Earth with direct motion in an elliptical orbit. The Earth occupies one focus of this orbit, the plane of which is inclined about 5 degrees to the plane of the ecliptic. In other words, if we suppose a globe with the Moon's orbit for its equator, about $\frac{1}{12}$ of a whole rotation round one of its equatorial diameters as an axis would be enough to bring its equator into the plane of the ecliptic, supposing its centre to be in that plane.

**177.** The time occupied by one rotation of the Moon upon its axis is equal to the time occupied by one of its revolutions about the Earth; and this time is somewhat over 27 days. The equality of the times of the Moon's rotation on its axis and revolution in its orbit keeps a large part of one half of the Moon always turned towards the Earth, and a large part of the other half always turned away from it. We may say, although not quite accurately, that the Moon always turns the same side to the Earth. Some people find a difficulty in understanding why, under these circumstances, the Moon should be said to rotate on an axis. To get over this difficulty, it is only necessary to remember what has been said of real motions. If a man walks round a tree, facing northwards all the time, he will be facing towards the tree when

he is south of it, and will have his back towards it when he is north of it. Now if we are considering his movements with regard to the points of the compass, we shall not resolve his movement into two, but consider it a single movement round the tree, performed without any rotation. But if we are considering his movements with regard to the tree, we may resolve it into two, one movement round the tree, and one movement of rotation. This is what we should do if we were considering, for instance, the movement of a wheel placed with its axle north and south, and having a retrograde motion on that axle just equal to the Earth's direct movement of rotation. We should not be likely to say that such a wheel revolved round the Earth's axis without rotating, although we might if we did not consider it part of the Earth. On the other hand, suppose that a man walks round a tree in the ordinary way, with his left side, for instance, always towards the tree. In this case, we do not usually resolve his movement into two, because we consider it simply with regard to the tree. But if we consider it with regard to the points of the compass, we see that the man has been facing to all of them in turn during his circuit round the tree; therefore his movement must be resolved into two, one of these being a movement of rotation. We do not consider a mountain on the Earth's equator as revolving every day round the centre of the Earth and also rotating on an axis of its own, but we might if we did not regard it as part of the Earth. The Moon has a similar movement, performed, as we have seen, once in 27 days; and as the Moon is not part of the Earth, the accepted laws of motion require us to resolve this movement into one of rotation and another of revolution about the Earth. The need of doing so becomes very evident when we observe that the motion of the Moon about the Earth is not uniformly quick. According to the second law of Kepler (150) the Moon must move quickest in its orbit when it is at that end of its orbit nearest to the focus occupied by the Earth. It is then said to be in **perigee**; and in **apogee**, or at the opposite end of its orbit, it of course moves slowest.

But its rotation on its axis keeps on very nearly at the same rate, so that although the time in which the two movements are completed is the same, the time in which the Moon passes over a quarter of its orbit ending or beginning at perigee is less than the time in which it completes a quarter of a rotation. On such occasions, therefore, its motion round the Earth outruns its rotation a little. If a man walks round a tree in the ordinary way, and at some part of his course walks quicker than before without changing front any quicker than before, he will begin to turn his back upon the tree. This answers to the movement of the Moon in perigee; in apogee the opposite effect takes place; and accordingly we have somewhat different views of the Moon at different times. But so far as our view of the Moon depends on the facts just noticed, we shall have the same view of it in perigee that we have in apogee. After passing its perigee it will first move comparatively fast in its orbit, but constantly slacken speed, so that by the time it reaches apogee, it will have lost as much as it has gained upon its movement of rotation. On passing apogee it will still lose for a time, but continually lose less, and presently begin to gain again. The times, then, at which our views of the Moon will differ most in consequence of its varying speed in its orbit are times when it is in certain places in its orbit, one between perigee and apogee, and the other between apogee and perigee. These places may of course be calculated mathematically, but cannot be readily described except in mathematical language. It may here be noticed that the Sun, or any celestial object, may be said, like the Moon, to be in perigee when it is nearest to the Earth, and in apogee when farthest from it.

178. The Moon changes front to some extent, with respect to the Earth, in other ways besides this. To understand them, let us suppose, as before (176), one of the Moon's equatorial diameters in the plane of the ecliptic, and an imaginary globe with the Moon's orbit for its equator and one of its equatorial diameters also in the plane of the ecliptic. Now it is a singular fact that on this supposition the

two equatorial diameters just mentioned always lie along nearly the same straight line, so that if either the Moon or our imaginary globe were to be tilted so as to bring its whole equator into the plane of the ecliptic in the manner already explained, the line of the axis round which this movement took place would be about the same in both cases. But the two movements would be contrary to each other; that is, the Moon would have to tilt one way through about $\frac{1}{240}$ of a whole rotation and the globe would have to tilt the other way through about $\frac{1}{12}$ of a whole rotation in order to bring both their equators wholly into the plane of the ecliptic. Both these supposed movements are of a kind which cannot be called either direct or retrograde; for the axes upon which they are performed lie in the plane of the ecliptic, and so have no northern or southern ends with regard to that plane. But we have agreed to distinguish between direct and retrograde movements by means of the plane of the ecliptic (140), and therefore cannot conveniently distinguish between them by any other plane, even that of the Earth's equator.

179. We see, then, that if we suppose the Moon to tilt far enough to bring its equator into the plane of its orbit instead of into the plane of the ecliptic, it would have to move first through about $\frac{1}{240}$ and then through about $\frac{1}{12}$ of a whole rotation round one of its equatorial diameters as an axis. The sum of $\frac{1}{240}$ and $\frac{1}{12}$ is about $\frac{1}{15}$; but $\frac{1}{14}$ would come closer to the actual fraction of a rotation needed for the purpose just stated. To express the same fact in the usual manner, we say that the inclination of the Moon's equator to the plane of its orbit is nearly $6\frac{2}{3}$ degrees.

180. Now, since the Moon's poles do not take part in its rotation on its axis, and since the effect of that rotation on places near either pole is only to make them travel round it in a small ring, we sometimes see more and sometimes less of the region round either of the Moon's poles; and this would happen even if the movement of the Moon round the Earth were uniform and circular. If a man walks round a tree with one side always towards the tree, but always lean-

ing a little towards the south, then the top of his head will be turned somewhat towards the tree when he is north of it, and somewhat away from the tree when he is south of it. We have already seen, in considering the Sun (59), that sometimes one and sometimes the other of its poles is on the disk which it shows us ; and we may here mention that the inclination of its equator to the plane of the ecliptic, on which this effect depends, is about 7 degrees, or a little more than the inclination of the Moon's equator to the plane of its orbit round the Earth. The difference between the Moon and Sun in regard to the alternate appearance upon their disks of the regions close to their northern and southern poles is only that the Moon goes round the Earth, while it is the Earth which goes round the Sun.

181. The Moon's motion in its orbit is only one of the numerous movements into which its complicated course has been resolved. Another of these movements, which we are now to consider, is represented by a change of the following kind in the plane of its orbit. Suppose the imaginary globe, the equator of which is the orbit of the Moon, to have a precessional motion like that of the Earth, but quicker, so that it may be completed in the time of the Earth's nutation ; the change thus made in the plane of the Moon's orbit is that actually assumed to be taking place. The Moon itself has a precessional motion, completed in just the same time, so that whenever one of its equatorial diameters comes into the plane of the ecliptic the line of that diameter nearly agrees with the line drawn in the plane of the ecliptic across the orbit of the Moon (178). This last line is called the line of the nodes of the Moon's orbit ; and the precessional motion of that orbit, just mentioned, occasions what is called the retrogradation of its nodes. The word precession is usually employed only in speaking of those changes in the view we have of celestial objects which are occasioned by what may be called the retrogradation of the nodes of the Earth's equator, as described above in different terms (167). In like manner, the precessional motion of the Moon itself may

be called the retrogradation of the nodes of its equator. Not only, then, does the Moon rotate once on its axis in the same time in which it goes once round its orbit, but the nodes of its equator retrograde, generally speaking, with the nodes of its orbit. These two remarkable cases of agreement in period between different motions of the Moon have been carefully studied, but have never been fully explained, although certain suppositions with regard to the Moon's condition in past ages enable astronomers to account for the continuance of these agreements, if not for their origin.

182. The precessional movement of the Moon does not alter the inclination of its equator to the plane of the ecliptic, and therefore does not increase or diminish the amount by which it changes front, so to speak, towards the Earth. It merely alters the times at which we have views of the Moon differing as much as may be from each other. But any alteration of the inclination of the Moon's equator to the plane of its orbit alters the amount of this change of front. Such alterations result from changes either in the inclination of the Moon's orbit, or in the inclination of its equator, to the plane of the ecliptic. The effects of these changes may be compared to those of the change of obliquity of the ecliptic, and of nutation in latitude, in the case of the Earth. Their amount is never great.

**183.** The Moon is far enough from the Earth to make the views of it obtained at the same time in different terrestrial stations almost, but not exactly, the same. Moreover, we are carried past it every day, by the Earth's rotation; and when it first comes in sight, or, as we say, when it is rising, we can see a little more of the region near its preceding limb, and less of that near its following limb, than we can afterwards. When it sets, the opposite effect takes place. The words disk and limb, preceding and following, are used of the Moon and of other such objects just as they are of the Sun (49).

**184.** The Moon's orbit is regarded as in a constant state of change in various ways, and in particular as having a

direct revolution of its own, which carries the perigee completely round the Earth in about 9 years. This movement, like the retrogradation of the nodes of the Moon's orbit (181), does not affect the amount of what we have called the Moon's change of front to the Earth. This change of front, however caused, is called **libration**. The chief causes of the Moon's libration are, as we have seen, its varying speed in its orbit, and the inclination of its equator to that orbit. By means of this libration considerably more than half the Moon is turned towards the Earth at one time or another.

**185.** Many comparatively small modifications of the principal movements of the Moon have been noticed and studied by astronomers, and still continue to attract much attention; but they need not here be described. It is obvious that, in addition to its movements with respect to the Earth, the Moon accompanies the Earth in its movement round the Sun, and in such movements as may be common to all bodies of the Solar System. When we examine the movement of the Moon with respect to the Sun, without resolving it into a movement of the Moon round the Earth and a movement of both together round the Sun, we find that the Moon's path is constantly concave towards the Sun. That is, if a straight line is drawn between any two places in this path very near each other, the middle of this line will be between the Sun and the path. Accordingly, when the Moon is between the Earth and the Sun, its path bends towards the Sun rather than towards the Earth. If the Earth were stopped in its course about the Sun, the Moon would not stay in its neighborhood, but would go on circulating about the Sun in a less complicated path than that in which it now moves as the satellite of the Earth.

**186.** The Moon's distance from the Earth has been stated (21. 172) as about 30 diameters of the Earth, or something over a quarter of a diameter of the Sun. If we draw a circle to represent the Earth's orbit, large enough to reach across this page, the Sun must be represented by a dot less than $\frac{1}{100}$ of the width of the page; and the Earth and Moon, with

all the space between them, would not fill the width of the line drawn to bound the circle, if they were to be represented on the same scale ; so that the Moon's orbit would not appear distinct from the Earth's, but would be represented by the same line. The Moon's diameter is little over a quarter, its bulk little over a fiftieth, and its mass little over a hundredth of the Earth's. It thus appears that the Moon has comparatively little density.

**187.** The disk of the Moon is circular in shape, according to the most accurate measurements which have been made of it. So far as can be seen, then, the Moon is spherical, or almost spherical, in form. But its precessional movement, or the retrogradation of the nodes of its equator (181), could not be accounted for by the laws of motion on the supposition that its mass is evenly distributed about its centre. We must suppose, then, either that the density of its different parts varies considerably, or that it is spheroidal in form, with its longest diameter pointing to the Earth. This last supposition is generally accepted. Some have supposed the sides of the Moon nearest and farthest from the Earth to be of slightly different shapes. This theory has been supported on purely mathematical reasons, and also on conclusions drawn from the examination of photographs taken at such times that the effect of libration (184) might make the photographs differ from each other to some extent. In this manner, what are called stereoscopic pictures of the Moon, showing it as a globe and not merely as a disk, may be produced. However, neither the mathematical nor the photographic grounds for the theory of the unlikeness in shape between the two halves of the Moon have proved satisfactory to those who are competent to discuss questions of this kind ; but all agree that the Moon is not spherical, and that its longest diameter points, generally speaking, towards the Earth. Attempts have been made to account for this fact, but nothing definite is known upon the subject. Whenever the Moon's various movements have pointed its longest diameter slightly away from the Earth, it must begin to swing back towards

the Earth; and the movements thus set up have been called the real libration of the Moon. But this part of the Moon's libration is known rather by theory than by observation.

**188.** The visible parts of the Moon are undoubtedly solid. No distinct signs of any liquid or gas have been discovered on the Moon; and it is probable that no sea and no atmosphere exist there. This has given occasion for many guesses about the condition of the Moon in past ages, which need not here be repeated, since none of them can as yet be proved to be correct. It has been thought that liquids and gases may now exist upon the Moon in underground cracks and caverns, which is possible enough, or on the side never seen from the Earth, which is less likely. The Moon's mass is perhaps too small to keep any noticeable amount of atmosphere about it.

**189.** What we see of the Moon is a rugged and mountainous tract of country, which looks comparatively bright, with occasional darker and smoother districts, which got the name of seas and lakes before it was discovered that they were only valleys or table-lands. Some of them are farther from the Moon's centre, or, as we should say of similar terrestrial regions, are higher than others are. The Moon's mountains, or the lunar mountains, as they are often called, have been named after various men, some of these names being rather absurd. Among the lunar mountains are some which are nearly as high as the highest terrestrial mountains. Many lunar mountains have the appearance of terrestrial volcanoes; in fact, the volcanic appearance of the Moon is its most striking peculiarity. But none of the lunar volcanoes appear to be active at present; there are no signs of smoke or fire about them, and we must accordingly suppose that they have long been extinct. Astronomers have at times suspected that some of these volcanoes were still active, but their suspicions have not been confirmed.

**190.** The most powerful telescopes yet constructed show us the Moon as it would appear to the naked eye from a distance of about forty miles. But in thus magnifying the

Moon, we also magnify to the same extent that part of the Earth's atmosphere through which we look. Now this atmosphere is by no means perfectly transparent or perfectly alike in all its parts ; and when we look through it with telescopes fitted with eye-pieces of great magnifying power, our view is apt to be very indistinct and unsatisfactory. Consequently we never see the Moon nearly as well as we see objects forty miles off without the help of any instrument ; and with such eye-pieces as are usually applied even to large telescopes, we see the Moon in the proportions of a terrestrial object 300 miles or more away, and viewed without a telescope. No one, therefore, need expect for the present to be able to see animals or buildings upon the Moon, even supposing that there are any to be seen there. Considerable changes, such as the falling of great masses of rock, may occur in the lunar mountains, without being visible to us. There is no certainty that any change of this kind has taken place since men began to observe the Moon, although such changes have been suspected.

**191.** The rock of which the lunar mountains are composed does not seem to be very white or polished. If it were, the Moon would reflect more sunlight, and so appear brighter than it actually does. In fact, as any one may see for himself when the Moon is above the horizon by day, it is hardly as bright as a cloud lighted up by the Sun, and not much brighter than an ordinary terrestrial rock in full sunlight. The distance of the Moon, according to the principles of optics, does not make any difference in its brilliancy, so that we may fairly compare it with clouds and rocks. The lunar mountains, probably on account of the manner in which they catch the light as well as on account of the material of which they are composed, look brighter than the plains beside them ; and when the Moon is full, that is, when the Sun shines directly on the side of the Moon turned towards the Earth, the limb of the Moon looks brighter compared with the centre of its disk than it would if it were not for its mountains. Smaller hills would have the same effect, if they were

as steep as these mountains, which are thought to be ordinarily much steeper than terrestrial mountains. On the whole, then, the Moon sends us less light than we are apt to suppose when we see it by night. But we must remember that the western clouds often look very bright just after sunset, although there is then too much light in the sky to let us see the stars; so that it is not surprising that the Moon looks bright when the night has fairly begun. According to such comparisons as have been made, half a million full moons would not send us as much light as the Sun does. But particular parts of the Moon shine so brightly that we may presume that they consist of white or of polished rock.

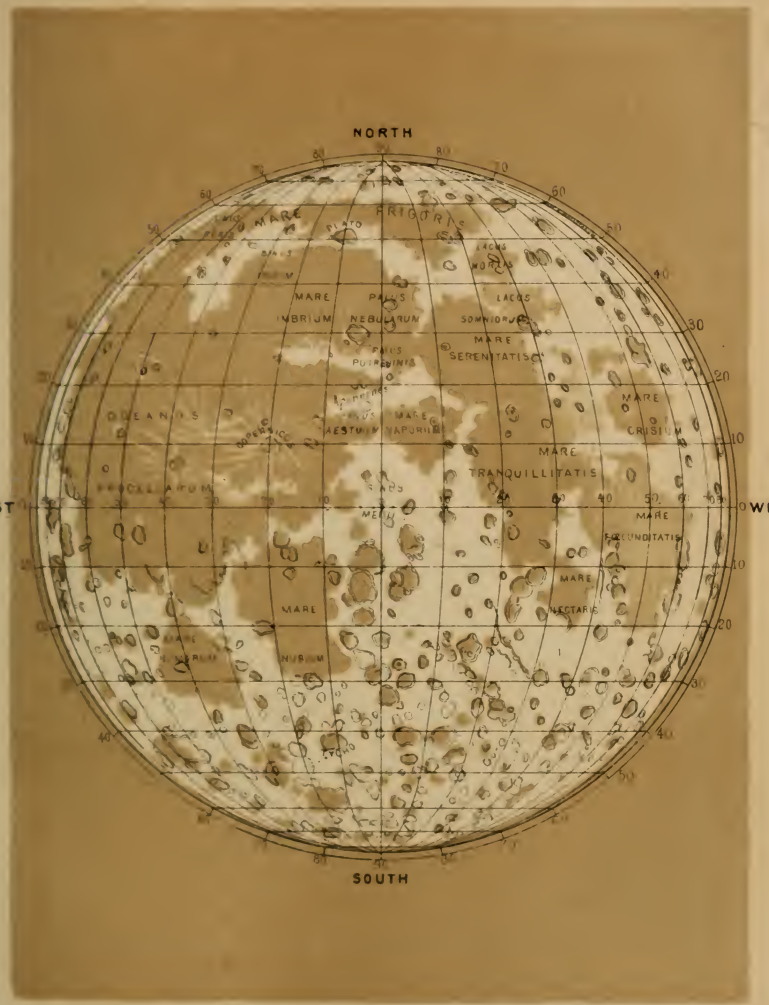
**192.** We get some heat from the Moon, but very little. This heat, so far as it makes its way through our atmosphere, which stops most of it, may be measured by the thermopile (97); and careful measurements of this kind have lately been made. They show that the Moon probably gives out no heat of its own. The rocks upon it reflect some of the Sun's heat to us, and besides this, they become very hot while the Sun shines upon them, as it does for a fortnight at a time, owing to the slowness of the Moon's rotation on its axis. They have little or no atmosphere in their neighborhood to stop part of the heat of the Sun on its way to them, and probably become much hotter than boiling water before the Moon's rotation begins to turn them away from the Sun. These hot rocks send out heat while they are cooling off as well as while they are exposed to the Sun. But the chief effect of the heat sent out by the Moon towards the Earth is to clear off clouds in the Earth's atmosphere, and even this effect is not very noticeable, although it can be perceived. When it takes place, the rocks and soil of the Earth can send out their heat without having it reflected back to them by the clouds, and so grow cooler rather more quickly than they do on cloudy nights. Hence the heat sent us by the Moon is more apt to make us cool than to warm us. The heat reaching us from a bright star is more easily perceived and measured than the very small amount which we receive

from the Moon ; but our knowledge of these minute quantities of heat is still very imperfect.

**193.** The Earth, since it is larger than the Moon, sends more light and heat to it than comes from the Moon to the Earth. In fact, the light by which, at the time of new moon, we see that part of the Moon's disk on which the Sun is not shining, is sunlight reflected from the Earth to the Moon, and then back from the Moon to the Earth. At such times, we may notice that the bright part of the disk seems to be part of a larger disk than that to which the faintly lighted part belongs. This is due to the blurring or spreading out of any bright object as it appears to our eyes. An effect of the same kind has been noticed above (80). Blurring of this kind is called **irradiation** ; there are other sorts of blurring, which are mostly due to the air through which we look.

194 Even the smallest telescopes show enough of the Moon's mountains and plains to make it an interesting object to examine. But little interest will be found in merely looking over the Moon even with the best telescopes. If our object is only to amuse ourselves, we must still compare the objects we see with their forms shown on a good map of the Moon, and learn to recognize them under the various appearances which they put on according to the different ways in which the sunlight falls upon them at one time or another. At times when the Moon is visible, but not full, we see with any telescope, and occasionally without one, that the boundary between that part of it on which the Sun shines and the remainder is uneven. The line of this boundary on the Moon's disk is called the terminator, and is uneven because the region it crosses is rugged, so that the sunlight is cut off from the low ground by the hills. In those places where the terminator crosses one of the plains, called seas, it looks more even than elsewhere. Beyond the terminator we usually see a number of bright specks, which are mountain-tops lighted up by the Sun, while the valleys lying between them and the terminator are in the shade. The bright regions near the terminator are marked with dark

*Plate IV.*

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The principal features of the Moon, many of which may be recognized by the naked eye, are shown in this figure. When the Moon is about three-quarters full, the range of mountains bounding the Sinus Iridum may be seen, without a telescope, to project beyond the neighboring parts of the terminator. Bright streaks are shown about the mountain Copernicus, but not about Tycho, where they could not easily be drawn. The places of the range called the Apennines, and of the mountain Plato (see Plate V.), are also shown in this figure.

*Plate V.*

This view is shown inverted, as it appears in a telescope. Part of the terminator appears in the lower right-hand corner. On the plain within Plato appear the shadows of the peaks along its left-hand border.

shadows cast by mountains, the height of which is shown by the length of these shadows. In fact, our knowledge of the height of lunar mountains depends on the accurate measures which have been made of their shadows. Farther from the terminator the shadows are shorter, because the mountains which cast them are turned more directly towards the Sun; so that many lunar mountains cannot well be distinguished except when they are near the terminator. But certain bright streaks on the Moon can be seen best under full sunlight, and are consequently plainest at the time of full moon. These streaks extend every way from some particular mountains, especially from one named Tycho.

195. The planet Mercury, which we are next to consider, is about $\frac{4}{10}$ as far from the Sun as the Earth is; and consequently, by Kepler's third law, it must go round the Sun about four times in one of our years. It is rather larger and much denser than the Moon, its diameter being about $\frac{3}{8}$ as long and its mass about $\frac{1}{16}$ as great as the Earth's. The eccentricity of its orbit is about $\frac{1}{5}$, so that at perihelion it is about $\frac{2}{3}$ as far from the Sun as at aphelion. The inclination of its orbit to the plane of the ecliptic is about 7 degrees; in other words, if there were a great globe enclosing the Sun, with the orbit of Mercury for its equator, that globe would have to make about $\frac{1}{50}$ of a rotation, round that one of its equatorial diameters which would lie in the plane of the ecliptic, in order to bring its whole equator into that plane. The line of the equatorial diameter used as the axis of this rotation is called the line of the nodes of Mercury's orbit. Mercury is probably spheroidal in shape; however, it is difficult to measure accurately the small disk which it shows us. Some observers have thought they could see indications of its rotation upon an axis. It probably does rotate, but we do not know what time its supposed rotation occupies, or, indeed, that it has any rotation. We cannot say positively, therefore, that it has an equator or poles. It is not known to have an atmosphere. Signs of mountains have been perceived upon it by some observers; but recent observations show only

that we know nothing about these mountains, and cannot even tell, when we examine Mercury with our telescopes, whether we are looking at land or clouds.

196. Venus is about $\frac{7}{10}$ as far from the Sun as the Earth is; it goes round the Sun, in a nearly circular orbit, in about $\frac{6}{10}$ of a year. The inclination of its orbit to the plane of the ecliptic is about $3\frac{1}{3}$ degrees; that is, the orbit would be brought wholly to the plane of the ecliptic by about $\frac{1}{108}$ of a rotation round the line of its nodes as an axis. The shape of Venus is spherical, so far as can be seen; its bulk is about $\frac{9}{10}$, but its mass only about $\frac{8}{10}$, of the Earth's, so that the Earth is a somewhat denser object than Venus. However, it is not known that the measurements yet made of the disk of Venus are any thing more than measurements of the distance between clouds on opposite sides of the planet. If this is the fact, Venus may not be quite so large a body as is supposed at present, and it may therefore be denser than we now take it to be. Venus is tolerably well known to have an atmosphere, and perhaps there are clouds in this atmosphere; but whether these clouds are numerous enough to shut out our view of the planet which they surround has never been discovered. Several observers have thought they saw signs upon Venus of mountains, and of a movement of rotation; but later observations show that these signs cannot usually be seen, and we must conclude that although Venus sometimes comes nearer to the Earth than any other of the principal planets ever does, we cannot find out much about it.

197. The reason why we know little of Venus and Mercury is that they are nearer to the Sun than the Earth is. When Venus or Mercury is on one side of the Sun, as seen from the Earth, it looks in a telescope like a half-moon, because the Sun lights up only half of that side of the planet which is turned towards the Earth; and when either of these planets is nearly between the Sun and the Earth, the Sun hardly lights up any part of it of which we are in sight. These changes, however, may sometimes help as well as hinder our observations; for many parts of the Moon are best seen at

other times than when it is full: the great difficulty in observing Mercury and Venus is that we never see them far on either side of the Sun. If we stand outside of a field in which there is a tree, we cannot usually see any thing in the field if we look far away from the tree. Suppose we are north of the field, and far away from it; then if we look east or west, we entirely lose sight of it. But if we go into the field, we can have the tree behind us and part of the field in front of us at the same time. Now, as we are always outside the orbits of Venus and Mercury, we can never see those planets unless we look pretty nearly towards the Sun at the same time. We must therefore observe them by day, or else at times when they have just risen or are near setting; and then we have to look through so much of the Earth's atmosphere that it is difficult to see any thing distinctly.

198. Planets nearer the Sun than the Earth is are called inferior planets. Venus and Mercury are the only inferior planets which are known; but black spots have sometimes been seen crossing the Sun's disk, which have been suspected to be small planets near the Sun. However, astronomers have looked carefully for such planets during total eclipses of the Sun, when they would be most likely to be seen in the Sun's neighborhood, without discovering any.

199. Planets farther from the Sun than the Earth is are called superior planets. Mars is the nearest of these to the Earth; it is about half as far again from the Sun as the Earth is, and occupies nearly two years in going once round the Sun. The eccentricity of its orbit is nearly $\frac{1}{10}$; that is, it is about $\frac{9}{11}$ as far from the Sun at its perihelion as at its aphelion. The length of a diameter of Mars is rather more than half as great as the length of one of the Earth's diameters; hence its bulk is over $\frac{1}{8}$, while its mass is less than $\frac{1}{8}$, of the Earth's. Its density, therefore, is less than that of the Earth. It is probably not exactly spherical; but how far its shape differs from that of a sphere has not yet been determined, as the measurements of different observers do not agree with each other. The orbit of Mars is little inclined to the plane of the ecliptic.

200. The Earth is evidently nearer to Mars when it is nearly between Mars and the Sun than it is at other times. But our distance from Mars, when the Earth comes nearly between it and the Sun, greatly depends on the place of Mars at that time in its somewhat eccentric orbit. If it is then near its perihelion, it will be nearer to the Sun, and therefore nearer to the Earth, by $\frac{1}{5}$ of its mean distance from the Sun, than it would be if it were then in aphelion. If the Earth is at its aphelion when it comes nearly between the Sun and Mars, it will pass somewhat nearer Mars than if it is at its perihelion; but the eccentricity of the Earth's orbit is small compared with that of the orbit of Mars. When Mars is nearest to the Earth, it is to be seen from that side of the Earth which is turned away from the Sun, as has just been shown; so that it rises about sunset and can be observed in the night. Besides this, the Sun then lights up that side of Mars which faces towards the Earth. Accordingly, much more has been learned about Mars than about Venus, although when Venus is between us and the Sun it comes nearer to us than we ever do to Mars. There are several dark spots on Mars, which have often been seen in the course of the last two centuries. These spots appear now to be of about the same shape which former observers give them in their drawings of Mars, made long ago; so that it is reasonable to conclude that we see something like firm land on Mars, and not merely clouds in its atmosphere. But Mars has an atmosphere, probably containing watery vapor, as is shown by observations with the spectroscope; and most likely there are times when the clouds in this atmosphere cut off our view of the land which it surrounds. This will explain why the spots on Mars seem sometimes to have various and changeable shapes, unlike those which are seen at other times. Those spots which have been often seen in about the same shapes, and which are therefore not likely to be the effect of clouds, are supposed by some observers to be oceans and seas. Most of the remainder of the disk has a reddish tint, so that Mars looks like a red star when viewed

without a telescope; this may perhaps be due to the color of its soil and rocks. By watching the spots of Mars we learn that it has a direct movement of rotation upon an axis. This makes the spots seem to cross the disk of the planet. The time in which Mars completes one rotation is little more than one of our days, and the statements of its amount made in recent times by different astronomers differ only a small fraction of a second from each other. From observations of this kind the places of the axis and equator of Mars have been pretty nearly made out, and it appears that the equator of Mars is inclined to the plane of its orbit about as much as the Earth's equator is inclined to the plane of the ecliptic. But it is more difficult to determine this accurately than to find the time required for one of the rotations of Mars.

201. Sometimes the region near the north pole of Mars appears upon the disk of the planet (59, 180), and sometimes the region near its south pole is the nearer of the two to the Earth. These polar regions, whenever seen, are observed to be white; and when either of them has been turned away from the Sun for several months by the planet's change of place in its orbit, the white spot on that part of Mars is larger than it is when the same region has been turned towards the Sun. This makes it probable that there is something on Mars like what we call snow and ice, and that the climate of Mars is warm enough to let this snow melt in the sunshine. However, the white substance seen about the poles of Mars cannot be proved at present to be exactly like terrestrial snow. The disk of Mars is comparatively bright all round the limb; this may be due to the effects produced by clouds.

202. Hardly any thing is known of the small planets between the orbits of Mars and Jupiter (108) except the form of the orbit of each of them and the position of its plane with respect to that of the ecliptic. The most eccentric of these orbits has the distance between its foci equal to about $\frac{1}{3}$ of the major axis; that which is most inclined to the plane of the ecliptic would be brought into that plane by about $\frac{1}{10}$ of a

rotation round the line of its nodes as an axis. However many asteroids there may be, the mass of all of them taken together must be small, as has been shown by the study of the movements of the other planets. The asteroids nearest the Sun are not much over twice as far from it as the Earth is; the mean distance of those which are most remote is about $3\frac{1}{2}$ times that of the Earth. A few asteroids look a little hazy or blurred, and have been thought on this account to have atmospheres; but most of them show no disks at all, and look just like faint stars, invisible except in good telescopes.

**203.** The four great planets, Jupiter, Saturn, Uranus, and Neptune, go round the Sun in orbits of little eccentricity, the planes of which differ little in position from the plane of the ecliptic. The mean distance of Jupiter is about 5 times that of the Earth; that of Saturn about $9\frac{1}{2}$, of Uranus about 19, of Neptune about 30, times that of the Earth. Saturn is therefore nearly twice as far as Jupiter from the Sun, and Uranus twice as far as Saturn; but Neptune is not much more than once and a half as far as Uranus. The comparative mean distances of all the principal planets as far as Uranus can be expressed pretty well by a rule commonly called **Bode's law**. According to this law, we count the distances of the planets in tenths of the Earth's mean distance. If we take 4 from the number of these tenths which denotes the mean distance of any planet beyond Mercury, double the remainder, and add 4 to the product, we shall have the mean distance, according to Bode's law, of the next planet beyond that which we begin with. Mercury is about 4 tenths and Venus about 7 tenths as far as the Earth from the Sun. Taking 4 from 7, we have 3; twice 3 is 6; 6 and 4 make 10, which is of course the Earth's mean distance counted in tenths of itself. Adding 4 and 12, we have 16 for the distance of Mars; 4 and 24 make 28; and the sum of 4 and 48 is 52, which represents Jupiter's distance very well. Saturn's distance does not fall far short of that denoted by the sum of 4 and 96, or 100; while 4 and 192 make 196, which answers well to the distance of Uranus. But 4 and 384 make

388, and the mean distance of Neptune is only 300 tenths of the Earth's mean distance. The want of a planet between Mars and Jupiter, to satisfy the rule just stated, was noticed before any asteroids were discovered; the mean distances of the first asteroids which were found are about 27 tenths of the Earth's mean distance, so that the discovery made it likely that the distances of any planets there might be beyond Uranus would conform to Bode's law; but when Neptune was discovered, its distance was found to be much less than would have been expected. We should have to add to Neptune's mean distance more than a quarter of its actual amount to make it as great as it would be according to Bode's law; the law, however, may be hereafter explained by more general laws, so as to show why it does not hold good in the case of Neptune.

204. Jupiter is the largest of the known planets, its diameter being over ten times as great as the Earth's. If its density were as great as the Earth's, its mass would be much over a thousand times that of the Earth. In fact, however, Jupiter weighs not much over three hundred times as much as the Earth, so that its density is small. But it is most likely that we see little of Jupiter except clouds in its atmosphere; and these clouds may extend so far as to make the planet seem considerably larger than it would appear without them. Within the clouds, therefore, there may be matter of considerable density. Jupiter occupies nearly twelve years in going once around the Sun.

205. The disk of Jupiter is crossed by dark streaks, called belts, which fade away towards the limb, and frequently change their form and color. But some of the spots and markings upon these belts last long enough to show very plainly that Jupiter rotates on an axis. Its movement of rotation is direct, and so rapid that a whole rotation is completed in a little less than ten hours. Each belt, speaking generally, is as far in one part as in another from either of Jupiter's poles; so that the belts are arranged like what are called zones in geography. The quick rotation of Jupiter probably has

something to do with this arrangement of its belts, and also with its general shape, which is so far from being exactly spherical that an equatorial diameter of the planet is greater than the polar diameter by about $\frac{1}{17}$ of its own amount. The spots of Jupiter from which its rotation is determined shift their places to some extent with respect to each other, so that the exact time of rotation is difficult to make out, as happens for a like reason in the case of the Sun (60). If the spots of Jupiter are caused by the difference of darkness between different clouds, or between clouds and the solid part of the planet, it is natural that they should shift their places considerably. However, different estimates of the time in which Jupiter makes one rotation agree together within a few minutes. Jupiter's equator lies nearly in the plane of its orbit.

206. Like Mars, and the other superior planets, Jupiter is nearest to us when the Earth comes nearly between it and the Sun. But even then, since it is over five times as far from the Sun as the Earth is, it is over four times as far as the Sun from the Earth ; so that its diameter does not seem $\frac{1}{10}$, but less than $\frac{1}{4}\frac{1}{0}$ of the Sun's. Without a telescope, then, we cannot see that it shows any disk at all ; it only appears to be a star brighter than any other except Venus. If we suppose it to be surrounded by clouds, we can see why it should look bright compared with Mars ; for most of the sunlight by which we see Mars has been twice through that planet's atmosphere, once on its way from the Sun to Mars, and again in coming from Mars to the Earth ; while the clouds around Jupiter probably reflect much sunlight to us before it has entered the denser parts of Jupiter's atmosphere. We have seen that an atmosphere is apt to absorb (51) part of the light which passes through it ; hence, although Mars is nearer the Sun than Jupiter, so that it must receive more sunlight in proportion to its bulk, and in fact does look like a bright star when it is nearest to the Earth, Jupiter looks still brighter even when the Earth is not nearly between it and the Sun. But if Jupiter were not far larger than Mars,

its brightness would not be enough to make up for its distance, and it would seem like a small star; not that it would then be dimmer than it now is, but because we judge of the brightness of seemingly small objects by the whole amount of light they send us as much as by the brightness of their separate parts. Jupiter is usually yellowish white, but sometimes reddish. In 1870, for instance, it was decidedly reddish for a time.

207. Jupiter has four satellites, which revolve about it as the Moon does about the Earth. These satellites are bodies of about the bulk of the Moon and Mercury, which are not very different in size, as we have seen (186, 195). Their orbits round Jupiter are almost in the same plane with Jupiter's equator, and as this equator is nearly in the plane of Jupiter's orbit, which does not differ greatly from the plane of the ecliptic (203), it follows that the orbits of Jupiter's satellites are pretty nearly in the plane of the ecliptic. Accordingly, these satellites are always near that plane; and as we also are always near it, we look at their orbits edgewise. For this reason Jupiter's satellites seem to us to move straight across the disk of Jupiter or behind it, always coming back to the disk after going a certain distance one way from it or the other. Consequently, they are often hidden from us in Jupiter's shadow or behind its disk, and we often see them or their shadows upon that disk. Their orbits, when made out by calculation from their observed movements, are found to be nearly circular, and their motion in these orbits is direct. There are certain fixed relations between their places and also between their movements, partly accounted for by known laws of motion. Their brightness changes considerably from time to time. Sometimes a satellite of Jupiter, when it passes between us and the planet, looks like a dark spot on Jupiter's disk; sometimes like a bright spot; and sometimes is too nearly of the same brightness with the disk to be seen at all. Some observers have thought that each satellite is always brightest at some particular part of its orbit, and from this it has been concluded that Jupiter's satellites rotate on their

axes, each making one rotation in the time it requires to go once round Jupiter, just as the Moon makes one rotation while it goes once round the Earth; other observers, however, think differently. But nothing is positively known of the rotation of any satellite except that which accompanies the Earth.

208. That satellite of Jupiter called the first is the nearest to the planet; the others are called second, third, and fourth, in the order of their distance from Jupiter. The second is the smallest, its diameter being rather less than our Moon's; and the third is the largest, considerably exceeding Mercury in bulk. The first is somewhat farther from Jupiter's centre than the Moon is from the Earth's centre, and goes round Jupiter once in less than two days; the fourth is nearly four times as far from Jupiter, and completes its revolution in less than seventeen days.

209. Saturn's diameter is about nine times as great as the Earth's; so that Saturn resembles Jupiter in size, as it does also in many other ways. It has belts less distinct than those of Jupiter, but like them; each of its rotations, which are direct, occupies little more than ten hours; its shape is like that of Jupiter, and its density is small; for its mass is less than 100 times the Earth's: but we must remember that in measuring the disk of Saturn, we may be measuring only the distance between clouds, and in this way may overestimate the bulk and underestimate the density of the planet. Saturn's equator is not so nearly in the plane of its orbit and in that of the ecliptic as is Jupiter's; it is about as much inclined to these planes as the Earth's equator is. Hence sometimes one and sometimes the other of its poles is turned considerably more than the opposite one towards the Sun; and its polar regions have been thought to change color to some extent, like those of Mars; but it seems unlikely that this is due to snow. Saturn goes round the Sun once in somewhat less than thirty years.

210. Saturn has eight satellites; they have been named instead of merely being numbered; but we know little about

*Plate VI.*

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This figure represents Jupiter as it appeared in the telescope (and therefore inverted) at Harvard College Observatory on the evening of February 2, 1872. The second satellite has just passed off the disk, on which its shadow is still visible. The equatorial region of the planet had a reddish tint, not represented here.

them except these names. Their motion is direct, and some of them have been thought to rotate once during one revolution about Saturn, for reasons like those which gave rise to the same opinion about Jupiter's satellites. The nearest to Saturn of its satellites goes round the planet in less than a day, and is only about half as far from Saturn's centre as the Moon is from the centre of the Earth ; its name is Mimas ; the farthest, called Iapetus, is nearly twenty times as far as Mimas from the centre of Saturn, around which it makes little more than one revolution in eighty days. Titan, the largest of Saturn's satellites, is nearly of the same size with the largest satellite of Jupiter ; the others seem to be bodies smaller than the Moon, and some of them can scarcely be seen even with large telescopes. Their orbits seem to be nearly in the same plane with the equator of Saturn ; but the plane of the orbit of Iapetus differs less from the plane of the ecliptic than do the planes of the orbits of the remainder.

211. Within the orbit of Mimas is a large flat ring, with its inner edge towards the equator of Saturn, which it completely surrounds. The part of this ring nearest Saturn reflects little sunlight to us, so that it has a dusky appearance, and is not easily seen, although it is not quite so dark as the sky seen between it and the planet. The outer edge of this dusky portion of the ring is at a distance from Saturn of between two and three times the Earth's diameter. Outside of this dusky part of the ring is a much brighter portion, and outside of this another, which is somewhat fainter, but still so much brighter than the dusky part as to be easily seen. The width of the brighter parts of the ring is over three times the Earth's diameter. To distinguish between the different parts of Saturn's ring, the outer part is called ring A. the middle part ring B, and the dusky part ring C. Between A and B is an apparently open space, near 2000 miles wide, which looks like a black line on the ring. Other divisions in the ring have been noticed at times, but this is the only one always seen with good telescopes at times when either side of the ring is in view from the Earth.

212. If Saturn's ring were in the plane of the ecliptic, it would always have its edge to us, and then we could scarcely see it at all; for it is perhaps less than 100 miles thick, and when its edge happens to be turned towards us, nothing can be seen of it except with the best telescopes; and even these show slight signs of it, if any. We could scarcely learn any thing about the ring from this view of it alone; but as the planes which bound it are about as much inclined to the plane of the ecliptic as is the plane of Saturn's equator, we get different views of it at different times. We can easily understand the sort of difference which there is between the appearances of Saturn's ring at one time and another, if we try some such experiment as the following.

213. Let some one hold a book with one side upwards and the other downwards at about the height of his head; that is, the book is to be placed as it would be if it were lying on the table, except that it is to be higher from the floor, so as to be nearly on a level with the eyes of any one standing in the middle of the room. Let the upper cover of the book be lifted about one-third as far as would be necessary to make it stand upright; in other words, let this cover be carried through about one-twelfth of a whole rotation about the axis on which it turns when the book is opened. Then, if we take the upper leaf of the book to represent the position of the plane of Saturn's orbit, the position of the cover will represent that of the plane of Saturn's ring. Now let the book be carried round the room so as always to keep its place with regard to the points of the compass; that is, if the upper edge of the cover was at first pointing north and south, let it be kept pointing north and south while the book is carried round the room. Any one who watches this movement from the centre of the room will always have the edge of the upper leaf of the book turned towards him; and the edge of the cover will also be turned towards him twice before the book has been brought back to its first place. But at all other times either the outside or the inside of the cover will be turned towards him. In the same way, if Saturn's ring had no inclination to the plane of

its orbit, its edge would always be turned towards the Sun ; while, on account of its actual position, its edge can be turned to the Sun only twice during the time which Saturn occupies in going once round the Sun. Hence one side of Saturn's ring is continually lighted up by the Sun for nearly fifteen years, while the other side remains in the shade. At the end of this time the edge of the ring has again been brought towards the Sun ; and afterwards, for another period of nearly fifteen years, the Sun shines upon that side of the ring previously in the shade, while the side formerly lighted up is now dark.

214. Accordingly, by an observer in the Sun, one side or the other of Saturn's ring would always be seen, except when Saturn was at one or the other of two opposite places in its orbit. But the edge of the ring may be turned towards the Earth more frequently than towards the Sun. To show this, let a book be carried very slowly round the room in the manner already described, while one observer watches it without leaving his place in the middle of the room, and a second observer walks round him at a short distance, moving the same way as the person who carries the book, and more quickly than that person. When the book has been brought nearly, but not quite, to one of those places in which the edge of its cover is turned towards the stationary observer, it will often happen that the second observer comes to a place from which he sees the cover edgewise, while one of its sides, the outside for example, is still in view from the middle of the room. As he continues his course, he will be for a short time in sight of the inside of the cover, but may perhaps again get a view of the outside of it before its edge has been turned towards the stationary observer. He may afterwards continue for a time in sight of the outside of the cover after the inside of it is in view from the middle of the room ; but his movement will soon bring him to a part of his course from which he will again see the inside of the cover. The edge of the cover will under any circumstances be turned towards him more frequently than towards the stationary

observer, although this may not happen exactly in the way just described; and the two observers will sometimes see different sides of the cover. But unless the observer who shifts his place goes far from the middle of the room, both observers will always see the same side of the cover except about those times when its edge is turned towards the stationary observer.

215. Accordingly, a terrestrial observer has the edge of Saturn's ring turned towards him more frequently than it is turned towards the centre of the Sun. He is sometimes carried by the Earth's motion from a place in view of that side of the ring on which the Sun is shining at the time to a place in view of its dark side; and the Earth's motion may bring him back again to some place in view of the bright side of the ring before the Sun has ceased to shine on it. Sometimes, too, the Earth may come opposite to the edge of the ring, and at once be carried back, by its movement in its orbit, to the side of the ring on which the Sun is shining; but when the dark side of the ring is in view from the Earth, the Earth will soon come up to the plane of the ring and pass through it, so as to have the bright side in view; it cannot in this case just come opposite to the edge of the ring and fall back again, as it can when it is on the same side of the ring with the Sun. All these facts may be readily shown by the experiment described above. About the time when the edge of Saturn's ring is turned towards the Sun, it may be turned in the course of a year once only, twice, or three times, towards the Earth.

216. When the dark side of the ring is in view, it appears as a black line crossing the planet; and on such occasions the sunlight reflected from the outer and inner edges of the rings A and B enables us to see traces of the ring on each side of Saturn, at least in places where two such reflections come nearly together. The seven inner satellites of Saturn, when the ring has its edge turned nearly towards us, may sometimes be seen between us and the ring or beyond it, looking like beads on or close beside the fine thread of light

to which the ring is then reduced. But at other times, since we look at the planes of their orbits, as well as at the ring, from one side or the other, and not edgewise, we see these satellites in various places around the planet; and their paths, as well as that of the outer satellite, do not appear straight like those of the satellites of Jupiter, and seldom carry them between Saturn and the Sun or Earth. The ring is of course most conspicuous at a time about half-way between the times when its edge is turned towards the Sun. Whenever its bright side is in view, its shape appears to us elliptical, owing to the effects of perspective, as we should call it in a picture. The parts of the ring called its ansæ are those about the ends of this seeming ellipse, one of them being on each side of Saturn. Ring C, which is somewhat transparent, is most easily seen at each ansa; but it appears as a dusky line where the inner edge of ring B comes between us and the main body of Saturn, or the ball, as it is often called. When the edge of the ring is turned away from us as much as it ever can be, ring A appears all round the ball; but the rings B and C always come between us and part of the ball, and are themselves partly hidden behind it.

217. How the ring of Saturn can keep its place about the planet is a question which it has always puzzled mathematicians to answer in conformity to the ordinary laws of motion. First it appeared that the ring could not be supposed to be made of solid matter all in one piece unless the masses of different parts of it were different, and unless at the same time the whole ring revolved rapidly round the ball; and this revolution of the ring was thought to be shown by observation as well as by calculation. But later inquirers satisfied themselves that even this explanation was not enough to show why the ring did not break to pieces, or fall down in some way upon the ball. They suggested, then, that the ring might be liquid. Still later, other mathematicians have satisfied themselves that the ring can neither be solid and in one piece, nor yet liquid, if it is to keep its place; and they conclude that it must be made up of a great number of small

satellites, each of which revolves around Saturn in an orbit of its own, but is always so near other little bodies like itself that it does not appear separate from them to observers at a distance. This theory is said to account for the division between rings A and B by considerations founded on the laws of motion and the observed place of one of the eight distinct satellites of Saturn. It will also explain the dusky appearance of ring C by the supposition that the small satellites nearest Saturn are not so closely crowded together as those beyond them; and the fact that ring B is brighter than ring A may probably be due to the great number of satellites which we should expect to find in the middle part of the ring. Recent spectroscopic observations show that the ball of Saturn has an atmosphere, but leave it doubtful whether the ring has one. Without the aid of any instrument, Saturn may be seen as a bright star.

218. Uranus is much smaller than Jupiter or Saturn; its diameter, however, is about four times that of the Earth. Its mass is only fifteen times as great as the Earth's, so that its density is about the same as that of Jupiter. Neptune is somewhat larger and heavier than Uranus, but not so dense. The time in which Uranus goes once round the Sun is over eighty years; Neptune occupies over one hundred and sixty years in one revolution. Nothing is known of the rotations of Uranus and Neptune, or of any difference in length between different diameters of either. Some observers have thought that they perceived spots on Uranus, but their conclusions with respect to its rotation do not agree with each other.

219. Uranus is known to have four satellites, and Neptune one. Other satellites have been suspected to accompany these planets, which have also been thought to have rings like the ring of Saturn.

220. The known satellite of Neptune is somewhat nearer Neptune than the Moon is to the Earth, and goes round Neptune once in about six days. Of the known satellites of Uranus, that which is farthest from the planet is about half

as far again from it as the Moon is from the Earth, and goes round Uranus once in less than a fortnight. The planes of the orbits of all these satellites differ considerably from the plane of the ecliptic; the orbit of Neptune's satellite would have to make about one-tenth of a rotation round the line of its nodes as an axis in order to be brought into the plane of the ecliptic, and more than twice as much rotation would be needed for that purpose by the orbits of the satellites of Uranus. An observer near Uranus, then, placed with his feet towards the plane of the ecliptic, would see the planet's satellites passing nearly over his head (140); so that the words direct and retrograde do not apply very well to their movement. But they would not pass exactly over the head of our supposed observer; and if he was on the northern side of the plane of the ecliptic, he could perceive their movement to be from his left to his right when they passed in front of him; they are therefore said to have a retrograde movement in their orbits. The movement of Neptune's satellite can be observed only with much difficulty; but it seems to be retrograde, like the movement of the satellites of Uranus.

221. Uranus can barely be seen, and Neptune not at all, without a telescope. Both these planets seem to have atmospheres; and it has been thought that some of the light we receive from them may proceed from incandescent matter belonging to them, and may not be merely sunlight reflected to us.

222. Jupiter and Saturn, also, are considered by some astronomers as probably hot bodies; but the light they send us seems not to be regarded by observers with the spectroscope as any thing more than sunlight. But, as we have seen, it is likely that this light comes from clouds brightly lighted up by the Sun.

## CHAPTER VI.

### NEBULÆ, COMETS, AND METEORS.

**223.** ANY cluster of stars too faint to be distinguished separately will appear to us, if it can be seen at all, as a whitish speck in the sky, which looks like one of the objects called nebulæ; and clusters of faint stars are actually called nebulæ until we are able to make them out to be clusters. But it is now generally believed that many of the cloud-like objects seen with the help of telescopes are not clusters of stars, but collections of luminous gases or clouds of fine particles of solid or liquid matter. When an object of this kind shines by light of its own, and is so far from us that it seems to move very slowly, if at all, it is always called a **nebula.** To be visible at all, it must be larger than a star, since its light is not brilliant; and some nebulæ certainly stretch over vast spaces in the universe; but no one can tell how large these spaces are until we have learned the distance from the Earth of the nebulæ which fill them. It is more difficult to determine the distance of a nebula than that of a star, because a nebula is an indistinct object, so that its place among the stars, as seen from the Earth, cannot be exactly made out; and the distances even of the stars are yet almost wholly unknown. But if some of the nebulæ are no farther from the Earth than the nearest of the stars whose distances are known, even then each of them must be large enough to reach over spaces much greater than that between the Sun and the Earth.

**224.** The spectroscope shows us that some nebulæ are composed of gases, perhaps unlike any which are known to chemists; other nebulæ seem to be partly solid or liquid; but perhaps they are wholly gaseous, their gases being for some reason so dense in places as to give out light like that

of an incandescent liquid. The forms of nebulæ are various; some show round disks, and may be spherical or nearly spherical in form. These are called **planetary nebulæ**. Others are in the shape of rings, and still others have a spiral or twisted form. Many, however, are less regular in shape than any of those just mentioned. There are also nebulous stars, or stars surrounded by more or less nebulous matter; and stars are frequently seen in most extensive nebulæ. These stars, of course, may be at a distance from the nebulæ in which they appear, either because they are between us and the nebulæ, or beyond the nebulæ. But it is likely that some of the stars are really in the nebulæ where they appear to be.

**225.** One nebula can be seen from the northern parts of the Earth without the help of a telescope; it is in the constellation Andromeda; but it looks like a little piece of the Milky Way until it is examined with a telescope. There is a great nebula in the constellation Orion, surrounding a group of stars which looks like one star until we see it through a telescope. The nebula about the star makes it look a little hazy, but not hazy enough to attract much attention. The telescope, however, shows us this nebula as one of the largest and most remarkable objects of its kind. The nebula around the variable star in Argo, already mentioned (100), is somewhat visible without a telescope.

226. While clusters of stars are most abundant along the Milky Way and in what appears to us as its neighborhood, nebulæ are scarcest in those regions, and abound in certain others. The reason of this is at present wholly unknown.

227. Attempts have been made to determine by means of the spectroscope (70, 94) whether certain nebulæ are moving towards or from the Solar System; but as yet these attempts have not succeeded.

**228.** The number of nebulæ not large enough or not bright enough to be seen from the Earth, but situated within that part of the universe over which our observations extend, is probably very great compared with that of the visible

nebulæ. Any object like a nebula which is near enough to the Sun to be considered as belonging for a longer or shorter time to the Solar System is called a **comet**; and several comets are usually noticed every year, although few are bright enough to be seen without a telescope. Some comets move in orbits much like those of the planets, except that these orbits are ellipses of considerable eccentricity. Comets of this kind are called periodical comets. They are all so faint that they can only be seen when they are near their perihelia (146); but their whole orbits can be determined from the observations made while they are in sight, so that the time when they will next be seen can be foretold. But most of the comets which are seen are supposed to pass through the Solar System only once, and their orbits, while they are passing through it, are of the kind called parabolic or hyperbolic. A parabola is an ellipse so eccentric that its length is out of all proportion to its width; and a body moving round the Sun in a parabolic orbit would keep on going farther and farther away from it, after once passing its perihelion, so that it would never reach any place which could be called its aphelion (146). A hyperbola is a line like a parabola in appearance, but differing still more from an ellipse; so that a hyperbolic orbit round the Sun, like one which is parabolic, never brings a body moving in it to its aphelion, and accordingly brings it only once to its perihelion. Now, as none of the numerous comets moving in parabolas or hyperbolas are likely to have been seen before, we must suppose that small nebulous bodies are very abundant in the parts of the universe through which the Solar System is passing, and probably elsewhere.

**229.** Comets appear to shine partly by reflected sunlight, like planets, but mainly by light of their own; for as they approach the Sun, the light and heat they receive from it make them partially incandescent, or perhaps only phosphorescent. At the same time, part of the solid or liquid matter which may belong to them is probably turned into gas. As they withdraw from the Sun, they become cooler, and give

out less light of their own, while they are also less lighted up by the Sun. But in this process of heating and cooling, the matter of which comets consist seems to become scattered, and probably never comes together again entirely. Hence a periodical comet, after passing its perihelion a number of times, may be altogether broken up into little bodies, each of which goes round the Sun in an orbit of its own, although the orbits of all will not differ much from each other. These little bodies cannot be seen at all, unless they come very close to the Earth; and hence a periodical comet may appear to grow fainter and fainter at each perihelion passage, and finally disappear, having been turned into a number of meteors (28). We do not know that all meteors are fragments of comets; probably some are, and some are not.

**230.** One effect of the action of the Sun upon a large comet is to make it throw out a shining streamer, or perhaps more than one; these streamers are sometimes about as long as the major axis of the Earth's orbit, but usually much shorter. They are called tails; but they are no more likely to be behind the main body, or head, of the comet than to be before it; for they are generally turned away from the Sun, so that when a comet is moving away from the Sun its tail goes foremost. The tail of a comet, however, is not always turned exactly away from the Sun, and comets have been seen with short tails pointing towards the Sun. The matter of which a comet's tail is formed seems to be thrown out on the side towards the Sun, and then to be thrown back beyond the comet on the other side. The tails of comets are usually more or less curved, and seem to be hollow. The explanation of these various appearances is still unknown; and it is particularly difficult to understand, when the tail of a comet is long and is carried rapidly half round the Sun about the time of the comet's perihelion passage, how it can be kept pointing away from the Sun. To account for this, it has even been guessed that the visible part of a comet may sometimes be surrounded by invisible gas, which becomes visible only when the sunlight reaches it through the comet;

so that the tail, on this supposition, would be a sort of luminous shadow of the comet. But this explanation has not proved satisfactory to those who have carefully studied the appearances presented by comets; and we must wait for more knowledge than has yet been gained before the various questions which may be asked about the tails of comets can be settled.

**231.** Not only the tail, but the whole, of almost every comet is so transparent that faint stars may easily be seen through it; and no comet has been found to have any mass large enough to be noticeable by comparison with the masses of the planets, or even of their satellites. Sometimes comets look like nebulous stars; that is, a comet of this kind consists of a rather bright and seemingly small spot of light, called the comet's **nucleus**, surrounded by a nebulous appearance known as its **coma**, with or without a tail. There are also comets which have only a coma, and no nucleus. The coma of a comet is generally a round object, but its form changes from time to time.

232. It is difficult to determine the exact shape of a comet's orbit, since we see the comet only while it is passing over a part of its orbit which is small compared with that which it traverses while it is out of sight. If a comet moves in a very long ellipse, the part of its orbit over which we see it move cannot well be distinguished from part of a parabola or hyperbola. It is usual to assume that a comet moves in a parabola, when its course cannot be exactly made out; so that some comets may really be periodical which are supposed to have parabolic orbits. On the other hand, when the orbit of a comet is presumed, from the observations made upon the comet, to be a long ellipse, we cannot be very sure that the comet will ever reappear. The orbits of some comets are much changed, according to known laws of motion, in consequence of the approach of these comets to any large planet. Thus, for example, a comet which appeared in 1770 had passed near Jupiter, and in consequence of its situation with regard to that planet its orbit had become an ellipse of

such a form that the comet could traverse the whole ellipse once in five and a half years. But after passing its perihelion it returned in its new orbit to the neighborhood of Jupiter, where its course was changed a second time, so that it never again came in sight of the Earth.

233. Many comets have retrograde motion; many, too, move in orbits the planes of which differ greatly from that of the ecliptic. But the larger number of comets known to be periodical have direct motion in orbits the planes of which do not differ more than the planes of some planetary orbits from the plane of the ecliptic. Comets are named by the dates of their appearances or of their perihelion passages; thus, the first comet of 1843 is the comet which passed its perihelion earlier in that year than any other which was observed. Periodical comets are also known by the names of the astronomers who either discovered them or showed them to be periodical.

234. The most remarkable of all recorded comets is perhaps the first comet of 1843, just mentioned. It was at one time bright enough to be seen by day, and its tail was of extraordinary length. But in these respects other comets may have equalled it; the most wonderful fact in its history was that at its perihelion the comet was only distant from the photosphere of the Sun by about one-fourteenth of the Sun's diameter. It therefore went through the atmosphere of the Sun, its speed being at that time so great that it occupied only two hours in going half round the Sun, and returning to the southern side of the plane of the ecliptic, on which side its whole orbit was situated except that part of it which formed, as we may say, a loop lying close round the Sun on the northern side of the plane of the ecliptic. The tail of the comet was accordingly whirled round in the course of a couple of hours, so as to point one way at the beginning and the opposite way at the end of this short time. It is almost impossible to suppose that the matter forming this tail continued to be the same throughout this change. The comet of 1843 may perhaps be periodical.

235. The sixth comet of 1858, called also Donati's Comet, was a conspicuous and beautiful object for several months towards the end of that year. It has been thought to be periodical.

236. The second comet of 1861 could not be seen from the Earth's northern hemisphere till just after it had passed its perihelion, when its long tail was unexpectedly seen about the end of June. The Earth is supposed actually to have passed through this tail; but as the tail of a comet doubtless consists of something much less dense than our atmosphere, it is not surprising that no noticeable effect was produced upon us by the encounter thus presumed to have occurred.

237. The first comet found to be certainly periodical is that called Halley's Comet. It appears about four times every three centuries, and was last visible in 1836. It will again be in sight about 1912. It seems to have been a very large and bright comet several centuries ago, and on more recent occasions it has appeared with a tail of considerable length.

238. Encke's Comet goes once round the Sun in about three and one-third years. No other comet is known to return so often as this. It is a faint comet, scarcely to be seen even with good telescopes. The time it requires to go round the Sun has been slightly but steadily growing less since its discovery. This has been thought to be due to the resistance offered to the comet by the ether, or by some kind of matter through which it may have to pass. It may seem strange to suppose that a comet is made to go round the Sun in less time than before by being hindered in its movements; but if its headway were stopped altogether, it would fall into the Sun; and if its headway is lessened, it will fall in a little towards the Sun, so that its orbit will be closer to the Sun, and therefore shorter, than it was before. This shortening of its orbit will make its speed greater, according to Kepler's third law; so that there will be two reasons why it should come round more frequently than at first to any part of its orbit. First, it has less distance to go; and secondly, its speed is in-

creased. These reasons will be more than enough to prevent it from being delayed in its return to its perihelion, for instance, by any resistance made to its movement by the ether. But it is not certain that this is the right explanation of the peculiar movements of Encke's Comet, which are still under discussion by astronomers.

239. Biela's Comet formerly went round the Sun once in about six and a half years ; it was scarcely ever to be seen without a telescope. Its orbit nearly crosses that of the Earth ; so that half a century ago it was shown that it would probably come into contact with the Earth sooner or later, as its orbit would be likely to change enough to bring it occasionally very close to the Earth's orbit, and as the Earth, on some occasion of the kind, might be passing along that part of its orbit which the comet was crossing. Biela's Comet, when seen in 1846, was found to have separated into two comets. These two comets reappeared in 1852, but they were not seen when they were looked for in 1859 or 1866. Before 1872, astronomers had learned that some at least of the objects called shooting stars might be considered as little fragments of the matter like that which composed some comets. It was also found by calculation that the orbit of Biela's Comet might have been changed enough, since the comet had been seen, to bring it near the Earth towards the end of 1872 ; so that when numerous shooting stars were seen on the evening of November 27, 1872, it was thought that they might belong to Biela's Comet, the matter of which was supposed to have become so much scattered as no longer to be visible at any considerable distance in the shape of a comet. On this supposition, the comet crossed from the northern to the southern side of the plane of the ecliptic about the time when the shooting stars appeared, in such a way that it would afterwards be out of sight from the northern parts of the Earth ; but from the courses taken by the shooting stars it was possible to judge whereabouts in the southern sky the comet would be seen, supposing it to be visible at all. Professor Klinkerfues of Göttingen, in Germany, immediately sent to

Madras by telegraph the information required in order that the comet might be looked for; and something having the appearance of a comet was actually seen at Madras near the place where it was thought that Biela's Comet might be. Cloudy weather, however, made it impossible to get observations enough of this object to determine whether it was really Biela's Comet or not. But it seems likely, at all events, that Biela's Comet is now nothing but a swarm of meteors.

**240.** Other periodical comets, too, are thought to be mainly or wholly clouds of the little objects to which the name of meteors is now usually given. As a comet of this kind breaks up, the meteors belonging to it are scattered, in the course of years, all along the neighborhood of the comet's original orbit; for though each meteor goes round the Sun as before, all of them do not go equally fast. Thus, by degrees, the comet may be turned into a sort of ring surrounding the Sun and revolving about it. We know that there are many rings of this kind, whether they have been formed from comets or not. The meteors which compose them are in most places not near enough to each other to appear even like a faint cloud in our telescopes, although that appearance may be shown by the part of a meteoric ring where the meteors are most crowded; and then the cloud which is seen may be called a comet. When meteors come into the Earth's atmosphere in the course of their movements, they are made so hot by their quick motion through it that they become incandescent and appear like moving sparks, which we call shooting stars.

**241.** Accordingly, if the Earth could be kept at any one of a great number of places in its orbit, a constant stream of meteors would be moving past it. If the Earth were deep in the midst of this stream, great numbers of shooting stars would be continually appearing on that side of the Earth turned towards the approaching meteors. But if the Earth were only just within the stream, where the meteors would probably be farther apart from each other, the shooting stars would be less abundant. Streams of this kind are supposed

to be often very wide and deep in comparison with the size of the Earth, so that while some meteors are crossing the Earth's orbit, other meteors belonging to the same stream are passing by it at a distance from it of many thousands of miles. So, too, a stream of meteors, especially if its course slants along that of the Earth, may take in so much of the Earth's orbit as to show us many shooting stars for several nights in succession. Every year, as the Earth comes to those places where its orbit is crossed by streams of meteors, we see shooting stars belonging to those streams. Over one hundred streams of meteors are thought to cross the Earth's orbit; and it is likely, therefore, that thousands of similar streams or rings are constantly moving round the Sun. As their orbits are generally long ellipses, their perihelia must be somewhat crowded together in the region near the Sun, while the major axes of their orbits point every way from the Sun, so that their aphelia are far apart. It is likely, then, that meteors are at all times more numerous in the neighborhood of the Sun, and perhaps in the neighborhood of any star, than at a great distance from it.

242. Only two of the streams of meteors crossed yearly by the Earth are remarkable enough to be separately mentioned here. Each of these streams has a comet belonging to it; but the Earth has never encountered either of these comets, so far as is known. The August meteors, as they are often called, form a ring which crosses that part of the Earth's orbit which we pass over early in August. The orbits of these meteors are considerably inclined to the plane of the ecliptic, so that each meteor moves with respect to this plane somewhat as a drop of water in the stream thrown by a fire-engine moves with respect to the window of a house into which the stream is thrown, when the pipe is held about on a level with the window. In this case, a ball dropped from the upper edge of the window-frame upon the stream would go through it quickly, provided it was too heavy to be carried away by the water. But if the stream is sent into a window high above the pipe from which it comes, the path of a ball

dropped from the top of the window-frame upon the stream will slant across it, and the ball will be comparatively long in going through the stream. Now, although the courses of the Earth and of the August meteors are such as to resemble those of the ball and the water in the first of these two examples, the Earth is several days among the meteors. The meteors of this stream are rather evenly distributed along it, so that many shooting stars are seen every year early in August, being usually most abundant on the evening of August 10. These shooting stars seem to move every way from a part of the sky in the constellation Perseus; an appearance due to the effect of perspective, as will be shown hereafter.

243. The other stream of meteors to be mentioned here can hardly be said to form a ring, because most of the meteors belonging to it are collected in the neighborhood of the comet which belongs to the same stream, so as to leave but few about other parts of this comet's orbit than that along which it happens to be moving. These meteors and their comet have their aphelia near the orbit of Uranus, and their perihelia about that part of the Earth's orbit where we arrive in the middle of November. They travel once over the whole course of their orbits in about thirty-three and one-fourth years, and the part of the stream where the meteors abound reaches about one-eleventh part of the way round these orbits, so that it takes about three years for this crowded part of the stream to pass any particular place. Accordingly, a great many shooting stars are seen from November 13 to November 15, for a few years at a time, and then only a small number each year at the same time for thirty years or so, until the crowded part of the stream comes to its perihelion passage again. The orbits of these meteors are not greatly inclined to the plane of the ecliptic, and their movement is retrograde, so that the Earth moves against the stream of meteors while passing through it. When any of these meteors appear as shooting stars, they seem to move every way from a part of the sky in the constellation Leo. They

were plenty in 1866, 1867, and 1868; so that probably few of them will be seen till about the end of the nineteenth century.

244 Besides the meteors belonging to rings or streams, which are called periodical meteors, there are others, called sporadic meteors, which are not known to belong to any particular meteoric swarm. Shooting stars are to be seen at all times of year; and some of the meteors (whether they are periodical or sporadic), which enter the Earth's atmosphere, are so large and compact that they make their way through it and come to the ground. It may seem as if the air could not stop any but very light meteors; but, in fact, a body moving many miles a second through even the thinnest air is very soon burned up if it can be set on fire, and if not, then crumbled to dust, by the heat produced in it by the resistance of the air to its progress. If it were not for the air, we should be in constant danger of being struck by meteors; but as it is, accidents of this kind are very rare, and it is seldom that a meteor is known to reach the land or sea. However, great lumps of stone and metal are sometimes found where a large and bright meteor has come down. These lumps are usually called aerolites; they occasionally weigh several hundred pounds. Some of them contain a great deal of iron. None have been found to contain any kind of matter not also found in terrestrial objects; but their materials are sometimes combined chemically in ways which differ somewhat from those in which terrestrial minerals are known to be composed. Hydrogen gas has been found in an aerolite, along with iron, the quantity of this hydrogen being sufficient to give rise to the supposition that the aerolite had been formed under a great pressure, and where hydrogen abounded; so that the iron became strongly charged with the gas. This has been thought to show that aerolites are produced by eruption from the Sun and other stars, where we know that iron and hydrogen are likely to be under great pressure. Examination of aerolites with the microscope has given rise to conjectures of a like kind. But the origin of all celestial objects is still very uncertain.

245. Aerolites usually first appear as large luminous objects, like shooting stars much larger than usual, — unless, as frequently happens, they fall by day; before reaching the ground they often explode with a loud noise, and their fragments are scattered over a considerable space. An occurrence of this kind was observed in June, 1866, in the north-eastern part of Hungary. A meteoric stone fell near Searsmont, Maine, in May, 1871.

246. Sometimes a large bright meteor is seen passing, which does not appear to come to the ground, or to explode. A meteor of this kind is often called a fire-ball. These meteors probably crumble to dust, like little shooting stars, before reaching the ground.

247. Bright shooting stars, and large meteors, often leave trains of little sparks behind them. These trains sometimes remain in view for many minutes after the appearance of the meteor.

248. The Earth, and other large objects, must be slowly increasing in size from the constant addition of meteoric dust and of aerolites. However, it would probably require thousands of years to add an inch in this manner to the Earth's thickness.

249. It has been thought that the heat produced in the air by the passage of meteors may be enough, or more than enough, to make up for the heat sent out by the Earth. But this seems to be only a guess, and geologists generally consider that there is reason to regard the Earth as a body gradually growing cooler.

250. The height at which meteors are seen, as determined by observations taken at different places about the same time, is occasionally over a hundred miles. Hence we conclude that the Earth's atmosphere extends at least to that distance. It is not likely that many meteors which have once entered the air pass out of it again. If any do so, their orbits must usually be so much changed by the resistance of the air to their movements, that if they were previously periodical, they are afterwards sporadic meteors.

## CHAPTER VII.

### PHENOMENA.

**251.** IN the preceding chapters, the attempt has been made to state the most important facts as yet discovered with regard to the material universe and the different kinds of objects which compose it. We can now go on to the explanation, by means of these facts, of various appearances which we notice around and beyond the Earth.

**252.** We will first consider exactly what we mean by the words up and down. If a heavy object of any kind is fastened to one end of a flexible cord, and hangs by this cord, without touching any other solid object; then, as every one knows, part of the cord will be straightened out by the weight of the object it supports; and when it has ceased to move, this straight part of the cord will reach upwards from the hanging object, or downwards towards it. A line which thus reaches exactly upwards or downwards is a **vertical** line.

**253.** If the Earth were an exact sphere of the same density in all parts, every vertical line would point downwards straight to the centre of the Earth (157), and upwards straight away from that centre. But owing to the spheroidal form of the Earth (159), as well as to its roughness and to the differences of density in different parts of it, vertical lines do not usually point exactly to its centre. However, they point nearly enough to its centre to allow us to consider them as pointing to it except when we wish to speak accurately. The word **down** may accordingly be explained as meaning towards the Earth's centre; and the word **up** as meaning away from the Earth's centre. The words up and down, when applied to objects outside the Earth, have different meanings in different places. As the North Star is nearly

above the Earth's north pole, it is nearly below the Earth's south pole. Of two men on opposite sides of the Earth, each is below the other, in the ordinary sense of the word below.

**254.** The words up and down, and others like them, are sometimes used in speaking of other bodies than the Earth. Thus, the Sun's chromosphere may be said to be above its photosphere, because it is farther from the Sun's centre; and an aerolite (244) which strikes any other planet than the Earth may be said to come down towards that planet before striking it. In one sense, the Sun may be said to be always below the Earth, because the Earth has a real falling movement towards the Sun; but it would be of no use to employ the word below in this manner. It is usually best to consider the word up as meaning only along a straight line from the Earth's centre through the place of something in regard to which the word is used; and to consider the word down as meaning only along a straight line from the place of something in regard to which the word is used through the Earth's centre. An object is in the **zenith** of any place when it is exactly over that place, and in the **nadir** of the same place when exactly below it.

**255.** Suppose a vertical line to be the axis of a rotating globe; then all parts of the equator of that globe will be on the same **level**; and the plane (137) in which this equator lies will be a level plane, or, as it may also be called, a **horizontal plane**; it will pass through the centre of the supposed globe, which may be anywhere we please in the vertical line. Every line lying wholly in this plane will be a horizontal line, and all its parts will be on the same level. The word horizon is in common use with the meaning of the ring where the sky, as seen from any terrestrial place, seems to meet the Earth. In its ordinary sense, the horizon is not usually horizontal, on account of the Earth's roughness; but if we have still water all around us as far as we can see, our horizon will be a horizontal line. But it will not be on the same level with the top of the water near us. If a raft could be

made so large as to be some miles across, and yet perfectly flat, its edges would be above the water which supported it: for the Earth is not flat, but round. Accordingly, when the horizon formed by still water is observed with suitable instruments it is found to dip, according to the usual phrase; or, in other words, to be below the level of the place from which it is observed. The fact that the horizon is always ring-shaped is sometimes called a proof that the Earth is round; but if the Earth were flat, we could see no farther one way than another, so that our horizon would still be a ring. But in this case there would be no such dip of the horizon as we actually find.

**256.** It follows from what has been said that no two places equally far from the Earth's centre can be on the same level, in the ordinary sense of that expression. Sometimes, however, we use the word level in another sense; as when we speak of the sea level, meaning the distance from the Earth's centre of some particular part of the ocean. But the different meanings of the words up, down, above, below, beneath, level, or in fact of any words, will not puzzle us if we take care, when we use any word, to know just what we mean by it.

**257.** Suppose a ridge of high ground to stand between two others, one to the east, the other to the west of it, all three ridges being equally high; or, in other words, reaching equally far from the Earth's centre. Then the tops of the eastern and western ridges will be below the level of the top of the middle ridge; hence the eastern and western ridges will be out of sight of each other. It is true that the top of the middle ridge is also below the level of the top of either of the others from which we choose to reckon; but if we reckon from the eastern ridge, for example, the top of the western ridge is so much lower than that of the middle ridge as to be hidden behind it.

**258.** In like manner, any terrestrial object which is moving away from us may disappear below the horizon while it is still near enough to us to be plainly seen if our view of it

were not cut off by the Earth. A traveller, as he approaches a range of lofty mountains, may first see their highest peaks, apparently resting upon the plain before him. As he goes on, lower but larger parts of the range come into sight. These he could have seen as soon as the higher mountain-tops, if they had not been below the level of part of the plain between him and them. Facts of this kind, like the dip of the horizon, make us aware of the globular form of the Earth. But to determine the Earth's exact shape, careful observations with delicate instruments are required. By such observations the relative position of horizontal planes in various parts of the Earth has been ascertained; and the form of the Earth has thus become much better known than it would be if we were placed at such a distance from it as to see at a glance that it is round; for then we could not measure it as accurately as we can by our actual surveys of its different parts.

**259.** The arched or vaulted appearance above us which we call the **sky** illustrates what has just been mentioned (255) with regard to the horizon. We have no means of judging how far we can see into the space around us; and accordingly we suppose ourselves, when we look away from the Earth, to see about as far one way as another. Hence we seem to be enclosed in somewhat such a hollow shell as was formerly called a crystal sphere (128); the color of which depends on the kind of light reflected to us (8) by the air and whatever may be floating in it. If no such light as this were reflected to us, the sky would appear black: and in fact it seems unusually dark when viewed from great heights upon mountains or in balloons, where the observer has much less air above him than he has at the sea level. As the proportions with respect to each other of the different kinds of matter in the air of any particular place are not always the same, the color of the sky changes more or less from time to time, even while it continues on the whole to appear blue; and when it is evenly clouded over it looks gray. We do not commonly notice that this gray light comes to us in

most cases from something within a few miles of the ground, while the atmosphere from which we receive the blue light called the color of the sky extends to a much greater distance from us than that of ordinary clouds ; and the gray cloud seems to be in the ordinary form of what we call the sky, since we usually know nothing of the comparative distances of its different parts from us.

**260.** We have already seen that besides reflecting light, the air absorbs it (51). Hence, if there were no atmosphere round the Earth, the Sun and other celestial objects would look brighter than they do ; but, on the other hand, we should lose a great deal of our ordinary daylight, which is sunlight reflected by the atmosphere, and diffused, according to the usual expression, around the various terrestrial objects. Diffused sunlight, reaching us when the Sun has lately set, or soon before it rises, is called **twilight**.

**261.** Heat, like light, may be absorbed and reflected. It would be much less difficult than it is to measure the heat reaching the Earth from the stars and from the Moon, if the atmosphere did not absorb much of this heat, especially that of the Moon (192), which is not an incandescent body like the stars.

**262.** Light is **refracted**, as well as reflected and absorbed, by the air. A familiar instance of the effect called refraction is the broken appearance of a stick held slanting and partly under still water. The part of the stick under water seems to slope more away from a vertical line than the part above water. This is because the light which comes through the water in any other course than a vertical one is turned still farther from a vertical course when it passes from the water to the air. Light passing along a slanting course through the air, on the other hand, is turned into a course more nearly vertical when it enters a level piece of water. Now the air alters the course of light coming to it from the comparatively empty space beyond it much in the same way as water alters the course of light coming to it from the air. As this light comes still nearer the Earth, the air through which

it passes continually increases in density and makes its course more and more nearly vertical. The consequence of this is that any thing at a considerable distance from the Earth seems to us a little nearer the zenith (254) than it really is. If it is already in the zenith, its place does not seem changed ; and the effect of refraction on any thing which seems high in the sky is too small to be perceived except by accurate observations. But the farther any thing is from the zenith of any observer, the greater is the change in his view of it which the atmosphere produces by refracting the light it sends to him.

**263.** We usually continue to see the Sun on a clear evening for some little time after it is really below our horizon ; for the air, by refracting the sunlight, enables us to look a little over the edge of the horizon, so to speak. We also see the Sun rise sooner than we should if there were no air to refract its light to us. Other celestial bodies, of course, are also actually kept in view longer than they would be if there were no air. Hence the Earth may in fact be exactly between two stars, one of which has risen before the other has set. So, too, the Moon may rise before sunset, while yet the Earth is between the Sun and Moon, so that the Moon appears darkened by the shadow of the Earth. Refraction does more than the dip of the horizon (255) to widen the prospect around the Earth which can he had from ordinary terrestrial stations ; but neither of these effects greatly changes the apparent distance of celestial objects from the horizon. The light coming from terrestrial objects on the sea level to an observer above that level passes through air continually lessening in density, and its course thus becomes more nearly horizontal as it goes on. Hence refraction lessens the dip of the horizon at sea, but lessens it very slightly.

**264.** It appears from what has just been said that unless an object is near the Earth it will always be in sight of one or the other of any two opposite places on the Earth, and may be in sight of both at once. If two men stand on opposite sides of a house, close to its walls, a carriage driven past the

end of the house may be out of sight of both men while it is crossing a strip of ground nearly as wide as the house. In the same way, if it were not for refraction, the Moon might for three or four minutes (for a longer time if the Earth's rotation were stopped) remain out of sight of both one and the other of two places on opposite sides of the Earth, where the view was not hindered by hills or otherwise. But this could not happen with the Sun, or with any other globe larger than the Earth ; such an object would begin to rise on one of the places of observation before it had set on the other. The stars are too far off to show us any disks (80) ; but many of them are probably much larger than the Sun ; so that a ring of stars which could all be seen at once from opposite terrestrial places would not take up a strip of sky having any noticeable width. Hence we may say that from any two opposite places on the Earth, an outlook towards all distant parts of the universe might be had at any given moment even without the help of refraction, or of the dip of the horizon. With these aids, the views obtained from opposite sides of the Earth partly overlap each other at a distance from the Earth about once and a half as great as that of the Moon ; but its exact amount at any particular time depends on the state of the atmosphere. A small object, then, as far from the Earth as the Moon is, may be at a given time below the horizons of two places on opposite sides of the Earth ; but all the celestial objects usually seen from any part of the Earth must always be above the horizon of one of these places or the other ; and some of them may be in view from both at once. If we regard the straight line joining the two places as a vertical line, the horizontal plane (255) which may then be considered as passing through the centre of the Earth is what is sometimes called the plane of the rational horizon of either of the places. The view from either place will extend, as has been shown, through the plane of its rational horizon at a moderate distance from the Earth ; and beyond that distance some objects on the lower side of that plane, as well as all on its upper side, will be above the actual

horizon. Accordingly, those stars which are in the zenith of either pole of the Earth are a little above the horizon of any part of its equator.

**265.** The absorption of light by the air near the Earth prevents us from seeing faint objects which appear to be low in the sky, and makes bright objects comparatively dim near the times of their rising or setting (51). The atmospheric disturbances which make the stars twinkle (106) and interfere in various ways with accurate observations of them, are also greatest along the horizon; so that a celestial object cannot be observed for astronomical purposes at the same time from exactly opposite terrestrial stations, as might be supposed from the explanation above. The effect of refraction increases so fast as we look lower, that the disks of the Sun and Moon, when rising or setting, often look oval instead of round; their upper limbs being less refracted than their lower limbs. Sometimes, too, these disks are curiously distorted by atmospheric disturbance. The reddish tint which they occasionally have is an effect of absorption.

**266.** We have already had several occasions to remind ourselves of the well-known fact that objects look smaller and closer to each other the farther they are from us. What are called effects of perspective depend upon this fact, and **celestial perspective**, or the perspective of objects seen in the sky, occasions appearances which require some explanation.

**267.** Most people have noticed, in crossing some long straight railroad track, that the lines of rail seem to slant towards each other in the distance, whichever way the spectator may look. In the same way, a number of long straight rows of small clouds, such as we sometimes see reaching across the sky side by side, seem farthest apart overhead, or wherever they come nearest to us, and slant towards each other as they approach the horizon on one side of us or the other. This slanting is generally only an effect of perspective; the rows of clouds, like the lines of rail just mentioned, are as far apart at one place as at another; but the distance between any two of them looks less the farther they

are from us. People not used to drawing are apt not to notice effects of perspective in objects near them. If they sit at one end of a room, for instance, they do not notice that the floor looks narrower at the farther end of the room than at the end where they are sitting; but others, who have been made to take notice of such facts by the careful practice of drawing, or in other ways, see the slant of the edges of the floor of a room as plainly as they see the slant of long lines of rail or of long rows of clouds. In the same way, a person who takes little notice of what he sees will sometimes say that the plate before him, as he sits at dinner, looks no larger to him than a plate of the same size on the other side of the table. This is only because he knows the plate nearest him to be actually no larger than the other, and pays no attention to what his eyes tell him. For this reason, people tell us that the Sun and Moon look to them as large as wheels, or plates, or other terrestrial objects; and it is often hard to make such people understand that a large wheel at a moderate distance from them looks smaller than a small plate close at hand. Every one will admit, however, that the Sun and Moon look about of the same size. Now the diameter of the Moon, as we have seen, is about one-fourth of that of the Earth, and the diameter of the Earth less than one-hundredth of the Sun's diameter; so that four hundred globes like the Moon must be put side by side, to reach from one side of the Sun to the other. In this case, then, the comparative distance of two objects makes a great difference in their comparative size, as judged by the eye. So does the comparative distance of any two objects, however small, and however near us they may be. If a plate six inches across is three feet from the eye while a plate one foot across is six feet from the same eye, then the apparent width of both plates is the same; as will be evident if the eye is in a line with the two plates. It is just as true, then, to say that the Moon looks as large as a plate as to say that it looks as large as a wheel; all we need to make these statements agree with each other is to find the distances from the eye at which a wheel and a plate of the

kinds meant to be used in the comparison must be placed in order only just to hide the Moon. If an experiment of this kind is tried, it will probably be found that the Moon or the Sun looks much smaller than was previously supposed. It may be worth while to add that doubling the distance of an object does not make its apparent width twice as small as before. This may seem to contradict what has been said above; but is really consistent with it, as is shown by geometry.

**268.** The reason why men commonly judge of the perspective and the apparent size of objects near them in one way, and of the perspective and apparent size of distant objects in another way, is that they have better means of learning the actual size and shape of objects near at hand than of others. The view obtained by one eye of the objects close at hand differs from that obtained by the other; so that even if the spectator does not move, the comparison of these two views, which is made too often and too quickly to be noticed, helps him to learn something of the objects seen. But when we move about, so as to get a variety of views of objects near us, and still more when we handle and measure them, we learn so much more of their real size and shape than we can by merely looking at them from one place, that we forget how they look. The sight of them then reminds us of certain facts about them, which we incorrectly suppose ourselves to see. Distant objects, on the other hand, are not seen as they are, but as they look; because we cannot even get different views of them without moving so far that we partly forget the first view before we have another considerably differing from it. In learning to draw, as has been said, we have to recover our power of seeing how objects look when they are near us.

**269.** One way of studying perspective is to look through a piece of glass at the objects beyond it and to mark down their outlines on the glass. In doing this, the head must be kept from moving, and only one eye used; for it will be found that the two eyes see different pictures. The drawing will represent the objects as they appear against the glass; and

such a drawing may be called their **projection** upon the glass. Objects may be projected in various ways upon other objects; but pictures are not apt to be exactly like copies of single projections of any kind; they are more often like copies of a number of separate bits of projections, and are more natural for being so, since we do not stand perfectly still while we are viewing a real landscape or a real group of people. But in looking at objects so far from us that we cannot alter their appearance noticeably by our own movements, what we always actually see is exactly like a projection of the objects we look at; this projection being made on any thing sufficiently far from us to prevent the disturbance of the projection by our movements. The projection may be supposed to be either between us and the projected objects, as if it were drawn on something transparent; or beyond the objects, just as a shadow, which is one kind of projection, is farther from the light which occasions the shadow than from the object which throws it.

**270.** The projection of one object on another, as appears from what has been said, is the shape traced out on that other object by a straight line fastened at one end and moved round the projected object so as always just to touch it. If the fixed end of the line (which is called the point of sight) is supposed to be farther away from the objects than any place which can be named, the projection is orthographic. A stereographic projection is a projection of a hemisphere, or of a part of it, on the plane by which that hemisphere is separated from the other, while the point of sight is in the middle of the outside of that other hemisphere. These projections, as well as others, made on the same general principles, are used in drawing maps. Celestial objects appear to us to be all at the same distance, since we cannot tell their distance by merely looking at them; so that they appear like their own projections on the imaginary object called the sky (259). This is likewise often true of distant terrestrial objects. When any object which we consider as projected on the sky moves directly towards us or directly away from

us, we cannot see by merely looking at it that it moves at all; in other words, the place of its projection on the sky does not change, though the projection grows larger or smaller as the object approaches or retires. If it moves in some other way, its projection on the sky will change place; in other words, it will seem to move; but this seeming movement will not be the same with any real movement which it may have. Suppose, for instance, that several small clouds pass overhead, moving straight forward and keeping their places with respect to each other. Their projections on the sky will rise from the horizon, or from somewhere near it, on one side, go farther apart from each other as they rise higher, and draw together again as they descend towards the opposite side of the horizon. The actually straight courses of the clouds must accordingly seem to be arches leaning away from each other at their summits, like those seemingly formed by straight rows of stationary clouds (267). All this may be shown more briefly and accurately by the aid of mathematical reasoning than in any other way, but perhaps not so plainly as in the way which has here been taken.

**271.** Sunbeams shining through openings among clouds, and made visible by their effect in lighting up the vapor or other contents of the atmosphere through which they pass, seem to spread apart more and more the farther they extend. This is of course an effect of perspective. When this appearance is seen, the Sun is sometimes said to be drawing water; an expression without much meaning, since water is obviously more likely to evaporate in full sunlight than under clouds. Sunbeams are also seen at times to extend from one side of the horizon to the other in the form of arches farthest apart from each other at their summits, like the rows of clouds already mentioned.

**272.** A similar effect of perspective appears in the streamers of the **aurora**, or northern lights, as the aurora is often called in the northern hemisphere, where it appears oftener in the northern sky than elsewhere. The auroral streamers of the northern hemisphere, when they are of a considerable

length, seem to spread apart for some distance from the northern horizon, and then begin to close together again, all pointing to a place somewhat south of the zenith. We conclude from this appearance that the streamers on the whole are straight, and as far apart in one part of their course as in another. They point the same way with a magnetic needle which has come to rest after being balanced, so that it can turn freely not only sideways, but also with a tilting or dipping movement. This circumstance, as well as others, shows that the auroral light is in some way due to magnetic or electric action; but its nature is still little known. One interesting theory, which seems now to be generally admitted, is that the disturbances on the Sun, which manifest themselves to us by the formation of spots and protuberances, occasion magnetic disturbances on the Earth, which result in auroras and peculiar movements of the magnetic needle; so that these terrestrial appearances become more frequent with the increase in frequency of the solar spots, and become less frequent as the number of solar spots decreases. Auroral displays, for instance, were frequent and brilliant, sometimes extending all over the sky, about the years 1860 and 1870; the light seen on these occasions being often of various bright colors, especially red, yellow, and green, instead of the greenish white of ordinary auroral light. Maxima of solar spots also occurred in 1860 and 1870 (63). It is likely that some of the appearances which, taken together, make up what we call the weather, are also periodical, and that their frequency changes with that of the solar spots; but nothing certain has yet been learned on this subject. The light clouds which have a hairy appearance and are called **cirri** have been thought, for instance, to be in some way connected with auroras, and to change with them in frequency.

**273.** When auroral streamers appear over a large part of the sky at once, their upper ends generally seem to be bent sideways so as to form a ring (called a **corona**) round that part of the sky towards which they point for the greater part of their courses. They sometimes remain steady for a time

and at other times change rapidly; and especially towards the end of an auroral display, flashes of light seem to shoot upwards along them. In ordinary auroras, the light is often mainly in the form of an arch with dark sky below it. When such arches are seen in the northern hemisphere, they appear in the northern sky. But there are other kinds of auroral arches and luminous belts seen occasionally in various parts of the sky, the light of which, when examined with the spectroscope, seems to show that they are appearances of a decidedly different kind from those of ordinary auroras. However, little has yet been discovered about them. The height of particular patches of auroral light has sometimes been estimated by means of observations made at the same time in different places. According to these estimates, some auroral light may be as much as five hundred miles above the sea level. If we suppose it to be occasioned by electrical discharges through gas of little density, we shall probably infer that there are gases in the Earth's atmosphere so light as to extend five hundred miles from the land and sea (174). On this estimate of the height of auroral light it is plain that a patch of it cannot be seen from places on the Earth opposite or nearly opposite each other (264).

**274.** Auroras are seen in the southern, as well as in the northern hemisphere; and appear there mainly in the southern sky. The name aurora originally meant the morning twilight, or dawn; and to distinguish them from this, the appearances commonly spoken of at present as auroras are sometimes called polar auroras; the aurora of the north being also named aurora borealis, and that of the south aurora australis.

**275.** The apparent paths of shooting stars illustrate what has been said of perspective, as do the sunbeams seen through clouds and the auroral streamers. If many meteors, all moving nearly the same way, plunge into the Earth's atmosphere at places far apart from each other, they will appear as shooting stars in different parts of the sky. But if we mark their tracks upon a chart, they usually seem to be parts of arches,

which, when completed, all pretty nearly meet each other at two opposite places in the sky. One of these places is on the side of the Earth from which the meteors come, and is commonly called the radiant point of the meteors. As we have seen, the radiant point of the August meteors is in Perseus (242), and that of the November meteors in Leo (243). The radiant point of the meteors of Biela's comet is in Andromeda, and the place opposite to it, where the comet was looked for at Madras (239), in Centaurus. The constellations serve (82) to point out the part of the sky where any thing is seen.

**276.** The appearances called halos, parhelia, and the like, are effects produced by vapor or by crystals of ice or snow floating in the air. A **halo** is a ring of light, sometimes colored, and surrounding the Sun or Moon. Halos are often seen round the Moon. Small halos are called **coronæ**. A parhelion (or a sundog) is a bright spot looking something like the Sun. A similar appearance produced by moonlight is called a paraselene. The Sun sometimes appears surrounded by an oval ring with a parhelion at each end and at each side.

**277.** The **zodiacal light** is a luminous appearance occasionally seen in the west after sunset or in the east before sunrise. It is broadest at the horizon, tapering upwards to a point, and lies along the zodiac, which may be described as that region of the sky occupied by certain constellations among which the Sun and Moon seem always to move. The zodiacal light is probably reflected from clouds of small meteors; but where these meteors are is not yet settled.

**278.** The **tides** of the ocean are generally included among astronomical phenomena. They consist of waves of extremely great width in proportion to their height. There are two principal tidal waves, the summits of which are on opposite sides of the Earth, and move round it regularly with a steady retrograde movement. The disturbance of these waves, produced by the land which they encounter here and there, starts a number of secondary waves, which occasion periodical currents moving backward and forward about the coasts

of the various continents. When two or more of these currents meet in a narrow bay, the tide there rises high and falls low; in other places the tide due to one current may be high when that due to another current is low; and in those places the rise and fall of the tide must be small. Differences of this kind often make the tides of one place very unlike those of another, not only in height, but also in other respects. On some shores there is only one tide a day; on others there are two, about equally high; and on others there are two tides, but one higher than the other.

**279.** What is properly called a tidal wave, then, is a wave a few feet in height and many miles across, so that it is too low and wide to appear to the eye as a wave at all; and it is also distinguished from other waves by coming back at regular times. A foolish habit has arisen, however, of calling any large and unexpected wave a tidal wave. This use of words is of course mere nonsense, and cannot be excused even by the great violence and speed with which the highest tides rush into some narrow bays and up some rivers.

**280.** The time and height of the tides depends upon the places of the Moon and Sun with respect to particular parts of the Earth, as will appear hereafter. There must be tides in the atmosphere, for the same reasons according to which there are tides in the ocean; and the currents of both air and ocean which are not tidal are governed largely by the Earth's movement of rotation, as the tidal currents are (163). The apparent movement of celestial objects which is due to the rotation of the Earth has already been partly considered (124), and we have now only to see how it differs in different terrestrial places. In considering this difference, we will pay no attention to any movements of the stars, apparent or real, except such as are due to the Earth's rotation. In fact, all the movements of the stars which are not due to the Earth's rotation are either too slow or too small to be easily noticed.

**281.** To an observer stationed at either pole of the Earth, the daily course of any star will seem to be a level ring. The

Earth's axis will point directly upwards and downwards. The stars nearly in a line with it will have scarcely any movement, so that those which are overhead at one time will also be overhead at any other time. If any star is exactly in the zenith, it will stay there, so far as its movements depend on the Earth's rotation; and any star which may be in the nadir will remain under the Earth. A star in the zenith of one pole must be in the nadir of the other. The stars which seem near the horizon of one pole also seem near the horizon of the other (264); so that their daily courses will be along the horizon of either of the poles. The higher a star seems in the sky, the smaller will be the ring in which it seems to move; but one part of this ring will seem to be on the same level with any other part of it. Under these circumstances, there can be no eastern or western part of the horizon (156). All parts of the horizon of the north pole are in the south, and all parts of the horizon of the south pole are in the north.

**282.** But if a traveller should set out from either of the poles, and move away from it as directly as he could upon the Earth, he would find, as soon as he had gone far enough to notice the change in his level, that the daily courses of the stars were sloping downwards behind him and upwards before him. The stars which at first moved along the horizon would now be above the horizon for that half of their courses in front of the traveller and would be below the horizon for the other half; so that they would rise on one side and set on the other. The part of the horizon where they rose could now be called the eastern and that where they set the western part. If the traveller should now turn so as to face the eastern part of the horizon he would have the north on his left and the south on his right. This is another way of distinguishing between north and south, besides that already mentioned (36, 156).

**283.** If the traveller continues his journey directly southwards or northwards, as the case may be, he will everywhere find that those stars which at first moved along the horizon

now rise in the east and set in the west. This amounts to saying that his journey changes his view of the stars in no other way than that in which he might change it (if the Earth were transparent), by simply leaning forward. As he goes on, each star which rises in the east daily stands higher in the sky half-way between its rising and setting, until at length it passes directly over his head. He is now on the equator; and the stars which were at first nearly in his zenith and nadir are now near the horizon behind and before him. If he goes on, the stars which were at first nearly over his head sink under the horizon behind him and those opposite stand higher and higher until they are over his head. He has now reached the pole opposite to that from which he started.

**284.** The stars which rise and set everywhere on the Earth except at places close to its poles, which always rise nearly due east and set nearly due west, and which are always nearly above one part or another of the equator, may be called **equatorial stars.** Their daily courses appear to be larger rings than those in which any other stars move, and lie along the horizon of either of the poles. The stars nearly in the zenith of either of the poles may be called **circumpolar** stars; all stars appearing at the north pole to be higher in the sky than the equatorial stars may be called northern stars; and all appearing at the south pole to be higher than the equatorial stars may be called southern stars.

**285.** At any place north of the equator more than half the daily course of each of the northern stars is above the horizon; some of these do not set at all (124); and the rest rise north of east and set north of west. More than half of the daily course of each of the southern stars is below the horizon; some of them do not rise at all; and the rest rise south of east and set south of west. To describe the appearance of the stars from any place south of the equator, we have only, in the last two sentences, to exchange the words north and northern for south and southern, and the words south and southern for north and northern. At the equator, the courses of all the stars seem to be upright arches, about

half the course of each star being above the horizon. The equatorial stars pass overhead, while both the northern and the southern circumpolar stars come into sight, although they are never far above the northern and southern parts of the horizon (264).

**286.** The Sun, in consequence of the Earth's yearly revolution round it, has not always the same apparent daily movement; it is in fact sometimes one of the northern and sometimes one of the southern stars, being an equatorial star whenever it is passing through the zenith of any place on the equator. If the equator lay in the plane of the ecliptic, the Sun would always be an equatorial star. For then the Earth's centre would always lie in the plane of the ecliptic, inside the ring formed by the equator; so that the line from the centre of the Earth to the centre of the Sun must always cross the equator at one place or another, through the zenith of which the Sun would be passing at the time when the line was supposed to be drawn.

**287.** We will begin by supposing the Sun to be always an equatorial star. In that case, the movement of the Earth in its orbit will be westwards from that place on the equator which is at any time beneath the Sun. This westward movement of the Earth will give the Sun an apparent eastward movement, only quick enough, however, to carry it round the place of observation once a year. Meanwhile, the rotation of the Earth will be giving the Sun an apparent westward movement, so quick as to carry it round the place of observation once a day. On the whole, then, the Sun's apparent movement will be westward, but not quite as quick as it would be if the Earth's movement in its orbit were stopped and only its rotation left.

**288.** As the day advances, the apparent movement of the Sun will carry it towards the western horizon. Meanwhile, the rotation of the Earth is bringing the place of observation more nearly into the track along which the Earth's centre is carried round the Sun. At sunset, therefore, the Earth's movement in its orbit has become nearly a downward move-

ment, so far as the place of observation is concerned. The Sun's apparent movement due to the Earth's movement in its orbit is accordingly upward, while the Earth's rotation gives the Sun the much quicker apparent downward movement which carries it below the horizon. Now let us suppose a star rising opposite the Sun just as the Sun is setting. The star's upward movement due to the Earth's rotation is just as quick as the Sun's downward movement due to the Earth's rotation; while the star, unlike the Sun, has no noticeable apparent movement due to the Earth's progress in its orbit. Consequently, the star must be rising a little quicker than the Sun is setting.

**289.** About midnight, the Sun will be near the nadir of the place of observation. The Earth's motion in its orbit will now be eastward, giving the Sun an apparent westward motion, which will slightly check its apparent eastward movement due to the Earth's rotation. The star will be high in the sky, and its apparent westward motion will not be checked by any apparent movement eastwards. It will continue, then, to gain on the Sun.

**290.** About sunrise, the place of observation will be on the forward side of the Earth as it moves along its orbit. The rising of the Sun will be slightly checked by this movement, while the setting of the star opposite will not thus be checked. Accordingly, if the star rose just as the Sun was setting (leaving the effect of refraction out of account), it must set a little before the Sun rises.

**291.** In the course of time, then, as the star is constantly gaining on the Sun, it will overtake and pass it. At the end of a year from the day when it was opposite to the Sun it will again be opposite to it, having apparently, during this time, gone round the place of observation once oftener than the Sun has gone round it. That is, there would be one more day in the year than there is, if we counted days by the rising or setting of the stars instead of by the rising or setting of the Sun. It appears from this that the period (119) of the Earth's rotation is less than what we ordinarily call a day.

Each day is prolonged for about four minutes by the effect of the Earth's movement in its orbit.

**292.** Another result of the fact that the stars are continually gaining on the Sun is that the stars which we see in the evening are not the same from day to day. At any particular hour of the evening the stars are a little farther advanced in their daily courses than they were at the same hour the evening before. Those which were then just setting are now below the western horizon; and some are just rising which were then below the eastern horizon. As the seasons change, therefore, the appearance of the evening sky likewise changes (82).

**293.** The apparent movements of any celestial object which are due to the changes of the plane of the ecliptic, or to the Earth's movements to one side of that plane or the other, are too small to be perceived except by close observation. We may therefore suppose for the present that the centres of the Earth and Sun are always in the plane of the ecliptic. But the Sun is not always an equatorial star, as we have been supposing it to be. Only one at a time of the Earth's equatorial diameters lies in the plane of the ecliptic (166); and it is only when the equatorial diameter lying in the plane of the ecliptic happens also to point to the Sun that the Sun is an equatorial star. We have just seen that the motion of the Earth round the Sun gives the Sun only a slow apparent movement, which will not change its place much in the course of a day. Let us suppose, then, that the Sun on some particular day is in a line with that one of the Earth's equatorial diameters which lies in the plane of the ecliptic. In the course of the day the Earth's rotation will have twice brought into the plane of the ecliptic, one after another, all the equatorial diameters which we may suppose it to have; and if we disregard the effect of its motion in its orbit, we may say that each of these equatorial diameters has thus been twice pointed towards the Sun, so that the Sun has been once in the zenith and once in the nadir of every part of the equator. During this day, then, and in fact for some days before and after, the

Sun seems to move in the sky about as it would seem to move if the whole equator of the Earth lay in the plane of the ecliptic. If the Earth, like Saturn, had a ring round its equatorial portions, the edge of the ring would at this time be turned towards the Sun (212).

**294.** But as soon as the Earth has moved far enough in its orbit to make a noticeable change in the position of its equator with respect to the Sun, that one of its diameters which points to the Sun is no longer an equatorial diameter; and supposing the Earth to have a ring like that of Saturn, the Sun has now begun to shine on the northern or the southern side of the ring. This may be illustrated by the same experiment by which the various appearances of Saturn's ring, as seen from the Sun, were explained above (213); for the inclination of Saturn's ring to the plane of Saturn's orbit does not differ much from the inclination of the Earth's equator to the plane of the ecliptic. If that diameter of the Earth which points to the Sun is not an equatorial diameter, one of its ends must be in the northern and the other in the southern hemisphere. Let us suppose that the northern end of this diameter is the end nearest the Sun. Then the places which have the Sun in their zeniths in the course of a day are all north of the equator; and the Sun passes north of the zenith of every place on the equator when it is noon at that place. The north pole is in some part of that side of the Earth which is turned towards the Sun; so that the Sun is all day farther than before above the horizon of the north pole, and all day below the horizon of the south pole. Every day, as the Earth advances in its orbit, the places which have the Sun in the zenith, one after another, lie farther north than before; while the region round the north pole on which the Sun never sets, and the region round the south pole on which it never rises, are growing larger and larger.

**295.** When the Earth has travelled over about a quarter of its orbit since the time when the Sun was passing through the zenith of a place on its equator, that equatorial diameter of the Earth which lies at the moment in the plane of the

ecliptic has its ends equally far from the Sun. If we suppose the Earth to have a ring like that of Saturn, the edge of that ring must at this time be turned as much away from the Sun as it ever can be; for it is no more turned towards the Sun at one of the places where it crosses the plane of the ecliptic than at the other. Any farther advance of the Earth in its orbit will bring the edge of the ring more into the sunlight at one of these places, and turn it more away from the Sun at the other, so that the ring will be placed more nearly edgewise towards the Sun. At this time, then, the places which have the Sun in their zeniths in the course of a day lie as far north of the equator as any places through the zeniths of which it passes during the year. They may be considered as forming the northern boundary of the torrid zone, known as the Tropic of Cancer; although, strictly speaking, the Tropic of Cancer is a boundary line drawn round the Earth, so that one part of it may be as far from the equator as another, and so that it may pass in any particular year through the most northerly of those places through the zeniths of which the Sun passes in the course of that year (167). But for a few days at a time, once a year, none of the places which have the Sun in their zeniths will be much to the south of the Tropic of Cancer. At this time, too, the region about the north pole where the Sun continues all day above the horizon will take in the whole north frigid zone, extending as far as the Arctic Circle.

**296.** After this, the places which, one after another, have the Sun in their zeniths will be nearer and nearer to the equator; while the region of perpetual day round the north pole and the region of perpetual night round the south pole grow continually smaller. When the Earth has come into a line with the place from which we supposed it to set out and with the Sun, one of its equatorial diameters again points to the Sun. Afterwards, the places which, one after another, have the Sun in their zeniths, are south of the equator, until some place on the Tropic of Capricorn is that beneath the Sun. At this time, the Sun is all day long above the horizon

of any place in the south frigid zone, and does not rise at all in the north frigid zone, except near its borders by reason of refraction. Continuing its course around the Sun, the Earth comes to the place in its orbit from which we supposed it to set out, when a year has gone by since the time of its last passage through that place.

**297.** If the apparent direct movement of the Sun occasioned by the Earth's motion in its orbit were exactly contrary to the retrograde daily motion of all celestial objects, we could easily tell what appearances would result from both movements taken together. But as they are not exactly contrary, we will resolve the Sun's direct movement into two; one of them exactly contrary to its retrograde movement, and the other carrying it due north for about half a year at a time, and due south for the rest of the year (the words north and south having still the meaning in which they are usually applied to the Earth). When this northward or southward movement carries the Sun through the zenith of any place on the equator, it is said to cross the equator from south to north, or from north to south, as the case may be; and the times of year at which it crosses the equator are often called the **equinoxes**. The name equinox comes from the Latin words for equal and for night, and is accordingly applied to the time when the Sun's daily course is like that of an equatorial star, so as to lie about half above and half below the horizon of all terrestrial places not very close to the poles. The times when the Sun stops moving north and begins to move south, or stops moving south and begins to move north, are often called the **solstices**; the name of solstice being derived from the Latin words for sun and for stand, or stop.

**298.** When the Sun is a northern star, more than half its daily course is above the horizon of any place in the northern hemisphere, and more than half of it is below the horizon of any place in the southern hemisphere (285). Hence, while the Sun is a northern star, it will rise earlier and set later on places in the northern hemisphere, and will rise later and

set earlier on places in the southern hemisphere, than it does while it is a southern star. This will tend to make the northern hemisphere warmer than the southern while the Sun is a northern star, and cooler than the southern while the Sun is a southern star. But the difference in the lengths of time during which the Sun is above the horizon in different days is not the chief reason why one day is warmer than another; or else the northern parts of Greenland, where the Sun never sets all summer long, ought to be warmer at that time of year than places near the equator, where the Sun is never above the horizon for much more than half of its daily course (285). In fact, however, Greenland is a cold country all the year, although not so cold in summer as in winter; for although the Sun shines there long at a time, it never is high in the sky. The Tropic of Cancer is not much more than one-fourth of the way from the equator to the north pole. Now when the Sun is crossing the equator it is near the horizon of the north pole; and when it is over the Tropic of Cancer it cannot therefore be much more than one-fourth of the way from the horizon to the zenith of the north pole or of places near it; while, as seen from any part of the equator, the Sun must come once a day to some place in the sky not much farther from the zenith than one-fourth of the way from the zenith to the horizon.

**299.** There are two reasons why the height of the Sun in the sky should make a difference in the warmth we get from it. In the first place, much more of the Sun's warmth is cut off from us by the air when the Sun is low than when it is high; for heat, like light, is absorbed by any atmosphere through which it passes (74, 192). Accordingly, when the Sun is near our horizon, part of the heat sent out from it towards us goes to warm the air over places between us and that place which has the Sun in its zenith. But secondly, even if there were no air, the ground around us would be less warmed by the Sun than as much ground in a place from which the Sun seemed higher in the sky. If a fence stands on level ground, the number of its posts which we should

pass in a hundred steps taken alongside of the fence would be greater than the number we should pass in a hundred steps of the same length alongside of a fence standing on sloping ground and having upright posts as far from each other as those of the first fence. So, too, if a shower of rain falls vertically on a hill at the top of which there is a piece of level ground, more raindrops must fall on a square yard of the level top of the hill than on a square yard of the sloping ground on its sides. Again, if any flat object stands nearly edgewise to the point of sight in a projection of any kind, it will be represented in the projection as a much smaller object than another which is really no larger, but which nearly faces the point of sight (270). All these examples show that a level piece of ground facing the Sun, or, in other words, having the Sun in its zenith, will get more heat from it than a level piece of ground of the same size standing nearly edgewise to the Sun, or, in other words, having the Sun near its horizon. If a projection of the Earth should be made, with the point of sight taken anywhere on the Sun, the shapes of the countries which had the Sun high in their sky at the time of the projection would be pretty correctly shown, while the places which had the Sun low in the sky would be much crowded together round the edge of the projection.

**300.** The course of the seasons, then, depends chiefly on the height in the sky which the Sun daily reaches at different times of year. In the torrid zone all times of year are hot, because the Sun passes every day not far from the zenith. In the middle parts of the temperate zones the summer is hot, because then the Sun daily passes near the zenith, and the winter is cold because the Sun then never rises far above the horizon. In the frigid zones the weather can seldom be called hot, because the Sun is never high in the sky, although it is so long above the horizon in summer that the weather then is much less cold than in winter. The hottest weather of summer usually comes somewhat later than the day on which the Sun passes nearest to the zenith; for the ground and air require time to become heated, and also require time for

becoming cool again. In like manner, the greatest heat of any particular day comes some hours after noon.

**301.** Until recent times, all highly civilized nations of whose history any record has been preserved have lived in the north temperate zone or in the northern parts of the torrid zone. Accordingly, the names which are usually given to the equinoxes and solstices are suited to the seasons of the north temperate zone. The equinox at which the Sun crosses the equator from south to north is called the vernal (or spring) equinox; the solstice at the time of which the Sun is in the zenith of some place on the Tropic of Cancer is called the summer solstice; the following equinox is called the autumnal equinox, and the next solstice is called the winter solstice.

**302.** If the time when the year should be considered to begin were now to be settled for the first time, it is likely that the vernal equinox would be chosen for this purpose. But it is always inconvenient to make changes in any arrangement which has once come into use; and when the first satisfactory plan for keeping particular months to particular seasons was contrived, it was thought best to begin the first year in which the plan was tried at the time of the first new moon after a winter solstice, although the plan itself had nothing to do with the Moon. Accordingly, the winter solstice still comes a little before the end of every year, although we do not reckon the beginning of the year by any new moon. Hence the summer solstice comes towards the end of June, and the equinoxes towards the ends of March and September.

**303.** The Earth's orbit is so situated at present that the Earth passes its perihelion about the beginning of the year, and its aphelion early in July. It is therefore nearer the Sun in the winter than in the summer of the northern hemisphere. But the eccentricity of the Earth's orbit is too small (146) to allow this circumstance to make much difference in the warmth of the weather at different times of year or in different parts of the Earth; although a sunny day in December

in the southern hemisphere is no doubt likely to be still hotter than a sunny day in June in the northern hemisphere.

**304.** Since the Earth moves quicker in its orbit the nearer it is to the Sun (148), the time from any vernal equinox to the next autumnal equinox after it must be a little more than half a year. The exact times of the equinoxes and solstices in any particular year may be found in carefully calculated almanacs. For common purposes it is correct enough to say, as people usually do, that the vernal equinox comes on March 21, the summer solstice on June 21, the autumnal equinox on September 21, and the winter solstice on December 21. As February, which is the shortest month, comes just before March, this will agree with the fact just stated, that the time during which the Sun is a northern star is a little longer than that during which it is a southern star. But the time from the vernal to the autumnal equinox is still longer than the time from March 21 to September 21, so that we shall be more accurate if we put the solstices and the autumnal equinox a day or two later than the 21st of the months in which they come. Although the Earth now passes its perihelion about January 1, this will not always be the case, since the slow change of the Earth's orbit already mentioned (169) makes the time when the Earth passes its perihelion a little later every year than it was the year before. But this change is so slow that it would alter the time of the Earth's perihelion passage less than four days in a thousand years. The Earth's precessional movement (167) does more than the change in its orbit to increase the time from the winter solstice to the perihelion passage. The Earth's equator is turned edgewise towards the Sun, by the retrograde precessional movement, more frequently than would otherwise be the case. That is, the year is shortened a little by the Earth's precessional movement. Hence the Earth's perihelion passage would be later in the year every time it happened than it was the time before, even if the Earth's orbit did not change. But the change in this orbit and the precessional movement, taken together, would alter the time

of the Earth's perihelion passage less than twenty days in a thousand years; and the differences between the times of the equinoxes, solstices, and perihelion passages of successive years, as found in the almanacs, are chiefly due to the facts that the leap years are each one day longer than the others, and that the Earth's movement round the Sun is not exactly in the ellipse called its orbit, but is subject to certain perturbations (170).

**305.** We have now considered the effects upon the seasons, and upon the Sun's place in the sky, of its yearly movement northwards and southwards. The chief effect of its movement exactly contrary to the general retrograde movement of all celestial bodies is that the other stars seem to be always gaining upon it, as described above (291). But this lagging of the Sun among the stars is sometimes greater than at other times; and we will now consider why its rate changes.

**306.** When any object is regarded as having two movements at once, the amount of its whole movement for any length of time is commonly less than the separate amounts, for the same time, of its two movements added together; and supposing its whole movement to carry it over equal distances at two different times, while one of its two movements is greater at the first time than at the second, it does not follow that the other movement must be greater at the second time than at the first. Still, in the case we are to consider, it happens, as would naturally be supposed, that the greater is the northward or southward movement of the Sun while its whole movement comes to any particular amount, the less is its second, or lagging, movement; although the decrease of one movement will by no means be equal to the increase of the other.

**307.** Now the change of the Sun's movement from northward to southward, or from southward to northward, is not sudden, but gradual. That is, for some time before and after either of the solstices, the Sun moves little either northward or southward; while at either of the equinoxes its northward

or southward movement is a larger part of its whole movement than at any other time, and becomes less and less in proportion to its lagging movement as it approaches the next solstice. It lags most at the solstices, then, and least at the equinoxes, in proportion to its whole direct movement at those times.

**308.** The whole direct movement of the Sun is quicker the nearer the Earth is to its perihelion; for not only does the Earth move quicker the nearer it is to the Sun (148), but the greater is the Sun's apparent movement due to the Earth's movement round it; just as the objects nearest to a moving railway train seem to its passengers to move quicker than others at a greater distance. Since the Sun's whole direct movement is thus, in our times (303), quicker while the Sun is a southern star than while it is a northern star, both its northward and southward, and also its lagging, movements are on the whole greater from the autumnal to the vernal equinox than for the rest of the year.

**309.** It follows, then, that the stars gain on the Sun more at the winter solstice than at any other time of year. They gain on it rather more than usual about the time of the summer solstice, although much less than at the winter solstice; and about the equinoxes they gain on it less than usual. If we compare the Sun's daily movement to the movement of the hand of a clock, we may say that it is fast losing at the time of the winter solstice, losing less at the time of the summer solstice, and losing still more slowly at the time of the equinoxes.

**310.** For all ordinary purposes, we must make our clocks keep time pretty nearly with the Sun; but it would be inconvenient, as well as difficult, to make clocks change their rates with the Sun. They are therefore so made that the number of days in a year counted by means of a clock is the same with the number of days in a year according to the Sun, although the length of every day is the same according to the clock, while according to the Sun different days have different lengths. Suppose that we have so good a

clock that it will run for a year at a time without either gaining or losing. We can set it so that on any day in the year when we please both its hands will point to twelve at the time when the Sun is highest in the sky. We may set it, if we prefer to do so, so that its hour hand points to six and its minute hand to twelve when the Sun is in the plane of the rational horizon (264); or so that it will agree with the Sun, as in the instances just given, at any time of any day in the year. The time actually chosen for this purpose is a little after the winter solstice; the reason of this choice depends on the terms used in practical astronomy, and need not be considered here. A little after the winter solstice, then, a sundial will agree with a good clock. But at this time the stars are gaining rapidly on the Sun; and considering the Sun as the hand of a clock, it is running unusually slow. Hence the sundial will lose time for several weeks, until it is about fifteen minutes slow of the clock. Then it will begin to gain on the clock, and will overtake it a little after the vernal equinox. It will go on gaining until the summer solstice approaches, when it will begin to lose; but its gain and loss at this time of year are comparatively small, so that it keeps within five or six minutes of the clock. Shortly before the summer solstice it will have fallen back so much as to agree with the clock again, after which it goes on losing for a time, and then gains rapidly, passing the clock and getting over fifteen minutes in advance of it before it begins to lose again. A year from the time chosen for the first agreement of the clock and sundial, they will of course agree, if the clock has kept good time.

**311.** A clock so regulated as to go on running in the manner just described, is said to keep **mean time**. If it is compared with the stars, it must be considered as losing one day in the year, or else the stars must be considered as gaining one day in the year. But by shortening the pendulum of the clock, we can easily make it go fast enough to keep up with the stars; or to speak more exactly, with any particular star we please; for, as we have seen, the stars as seen from the

Earth change their places slightly with respect to each other, by reason of their own real movements as well as by reason of real movements of the Earth, some of which belong to the whole Solar System, and not to the Earth alone. If we place a thin flat metal plate exactly north and south, and exactly vertical, fastening it so that it cannot change place with respect to the Earth, we may regard the Earth as the wheel of a clock and the plate as the hand carried by that wheel. Any star the daily course of which is a sufficiently large ring will answer to a mark to which the hand points upon the dial of the clock. We may now take a number of clocks of the usual kind, and try to regulate them so that one day according to these clocks shall be just equal to the time between the moments when the star comes opposite to the edge of the plate on one evening and on the next. We shall find that the intervals of time at which the Earth's rotation brings the plate back to the star are more nearly equal to each other than are the days marked by the best clocks that can be made. The Earth turns more uniformly than the wheels of our clocks, and those movements of the star which are not uniform are so small or so slow that they will interfere much less with the regular return of the plate to the star than the defects of our clocks interfere with their regular running. Still, since it is a known fact that stars have movements which are not uniform, it would not be convenient to regulate clocks by the movements of any particular star. When it is desirable that a clock should on the whole keep time with the stars, the effect of the Earth's precessional motion, as well as of its rotation, is taken into account ; and the clock is so regulated that it may run as nearly as possible at a certain rate found by calculation. The time which would be shown by a clock which always went exactly at this rate, and had been started exactly at the moment required by calculation, is called **sidereal time**. There are some stars according to which, on account of the Earth's precessional motion, the day would be a little shorter than it is by sidereal time ; but according to most of the stars, the day would be a little longer than it is

by sidereal time. However, as most of the stars lose little over three seconds a year on sidereal time, the error of a sidereal clock can easily be determined by observations of stars and a few simple calculations. It is easier to find the exact sidereal time in this way and then to calculate the exact mean time for the same moment than it is to get the mean time from the Sun, observations of which are not likely to be as accurate as observations of the stars. But at sea, the time is usually found by means of the Sun. Most of our clocks and watches, however, are regulated by means of comparisons made between some of them and the clocks regulated to sidereal time which are kept at astronomical observatories. A sidereal clock is of little use for the common purposes of life, because it gains one day in every year on an ordinary clock, and therefore never agrees with it except at the time of the vernal equinox, which is the time that has been chosen for this agreement, although any other time of year might of course have been chosen for it. About the time of the autumnal equinox, therefore, the day is half over by a sidereal clock when it is just beginning by a mean time clock.

**312.** Two clocks of the same kind, one of which is just north of the other, will always agree if they are running correctly, no matter how far apart they are upon the Earth. But if either is at all east of the other, the time shown by the eastern clock should be later than that of the other in proportion to their difference of longitude, as that word is used in geography. This, again, is a mere matter of convenience. Clocks might be set so as to show the same time in all parts of the Earth at any particular moment, and in some respects this arrangement would be more convenient than that now in use. But we are used to having the day begin at the time of midnight as shown by a mean time clock; and this time is nearly, although seldom exactly, in the middle of the night (310). The middle of the night at any place must be the time when the Earth's rotation has turned that place so far away from the Sun that a line from it pointing to the Sun's centre will cross the line of the Earth's axis. This cannot happen at

once in any two places, one of which is not due north of the other; so that if people agreed to begin the day at the same time all over the Earth, they could not all begin it about the time of midnight, which would be puzzling until they had grown used to the new arrangement. The mean time, or sidereal time, used at any particular place is called **local** mean time, or **local** sidereal time.

**313.** The local times of the ends of any diameter of the Earth must be twelve hours, or half a day, apart; unless this diameter is the axis, or polar diameter, at the ends of which there is, strictly speaking, no local time, for want of any mark of noon or midnight. All places north and south of the end of any diameter have the same local time with that end. Accordingly, the local times of two places, the shortest route between which, upon the Earth, leads directly over one of the poles, must differ by half a day. If two men travel from any place, one eastwards, and the other westwards, to some place the local time of which differs by half a day from that of the first place, then the day of the week or month, according to the traveller who went eastwards, will be the day after that which is the day of the week or month according to the other traveller's reckoning. For the traveller who went eastward has been through a series of places, the local time of each of which is a little later at any particular moment than the local time of the place next to it on the west. The difference of half a day between the places at the beginning and end of his journey will accordingly make his reckoning half a day later than the local time of the place from which he started, while for a like reason the other traveller's reckoning will be half a day earlier; so that the two reckonings will differ by a whole day. America was settled by Europeans who came to it westwards, while the European settlements in the East Indies were made by colonists who travelled eastwards. Consequently, when any traveller crosses the Pacific Ocean, he finds, if he comes from the East Indies to America, that the day which is Wednesday, for example, according to his reckoning, is called Tuesday in

the place at which he lands ; and if he comes from America to the East Indies, he finds that what is November 3, for example, by his reckoning, is called November 4 on shore. The name of any particular day at European settlements on islands in the Pacific Ocean depends on the places from which those islands were settled. This is one of the inconveniences of using local time, but it makes little trouble except that of learning the reason of it.

**314.** If a traveller should reach one of the poles of the Earth, and could determine its place with great precision, he could of course change his local time half a day by walking half round the pole, or a whole day by walking entirely round it. So too, if we ourselves could travel as fast as we can send a telegraphic message, we could change almost at once from one local time to another very different local time. If we had this power, we should find it easy to understand that our reckoning of local time is merely a convenient arrangement which might be changed without altering any astronomical or geographical facts.

**315.** Even at any one place different people may adopt different plans of reckoning local time. Sailors and astronomers, for instance, prefer to begin the day at noon rather than at midnight. Astronomers begin their days twelve hours later than most other people, so that the second of March, for instance, in astronomical mean time, is made up of the last half of the second and the first half of the third of March in ordinary civil time. According to Bowditch's Navigator, the nautical day begins twelve hours sooner than the civil day ; at present, however, sailors often follow the astronomical rule.

**316.** What is commonly meant by the time of day, among the civilized nations of European descent, is the local mean civil time of some important place in the same country with that where this time is spoken of. It would be troublesome to be always changing from one local time to another whenever we went from one house to another, or even from one town to another. Hence the local time of a large city, or

more accurately, of some particular place in a large city, is often used for many miles around the city. Thus, in the United States, we often hear of Washington time, New York time, and so on; especially when we travel long distances eastward or westward.

**317.** Astronomical clocks are generally made with dials showing twenty-four hours, so that the hour hand goes round its dial only once a day instead of twice, as in ordinary clocks. The hours of the day have sometimes been counted in this manner by other people than astronomers; and sunset has often been chosen for the beginning of the day instead of midnight or noon, but only in places where time was roughly reckoned by the sunset actually observed instead of by good clocks. The time shown by a sundial is called either true or apparent time; names which seem hardly applicable to the same thing. Now mean noon, as we have seen, never differs much more than a quarter of an hour from true or apparent noon (310); while the time of sunset, except at places near the equator, varies considerably at different times of the year.

**318.** The reason why the local times of sunset and sunrise change more than the local time of true noon with the time of year is of course the lengthening and shortening of the nights resulting from the Sun's northward or southward movement. This movement lengthens or shortens the night as much at one end as at the other; so that while it changes the times of sunrise and sunset, it leaves the times half-way between sunrise and sunset unchanged. These times must of course be very near the times of true noon and true midnight. Meanwhile, since the Sun's direct movement is not uniform, the remaining part of it somewhat changes the local time of sunrise and sunset as well as of noon and midnight. The course of these changes for any particular part of the Earth may be easily followed.

**319.** Suppose, for instance, that we are at any place in the north temperate zone of the Earth, and that the winter solstice is just passed. True noon now comes at twelve

o'clock (310), while sunrise comes considerably after six o'clock in the morning and sunset considerably before six o'clock in the evening; for the Sun is so far south that we see much less than half of its daily course (298). At this time the Sun's northward movement is slow (307), and it is losing fast as compared with the clock (309). This lagging of the Sun makes the sunrise, noon, and sunset of each day somewhat later than those of the day before it; while the slow northward movement of the Sun does little more, in making each sunrise earlier than the last, than is enough to balance the contrary effect just stated. But all that it does in making each sunset later than the last goes to increase the effect of the Sun's lagging behind the clock. Accordingly, the time of sunrise differs little from day to day for several weeks after the winter solstice, while the time of sunset grows later rather quickly.

**320.** As the vernal equinox approaches, the northward movement of the Sun becomes quicker, and begins to have much effect in making sunrise earlier and sunset later. Meanwhile, the Sun has begun to gain on the clock, which makes sunrise a little earlier still than it would otherwise be, and also makes sunset a little earlier, which tends slightly to check the effect of the Sun's northward movement in making sunset later; so that in early spring sunrise grows earlier more quickly than sunset grows later.

**321.** During the summer, the contrary effects of the Earth's place in its orbit and of the occurrence of the solstice (307, 308) keep the Sun in pretty good agreement with the clock (310), so that the times of sunrise and sunset depend mainly on the northward and southward movements of the Sun. In early autumn, however, while the Sun is fast gaining on the clock, sunset must grow earlier more quickly than sunrise grows later; and when the winter solstice is near, so that the Sun is in advance of the clock, but is quickly falling back to it, while the southward movement of the Sun is slow, the time of sunrise grows later more quickly than usual, while that of sunset has already grown nearly as early

as it is to be, and continues with little change for some time. The effect of the Sun's various movements on the times of sunrise and sunset at any particular place may be followed out by the help of the explanations already given. The northward and southward movements of the Sun can have no effect of this kind at places on the equator, where half its daily course is in sight whether it is a northern or a southern star (285). On the other hand, when the Sun has once risen at either of the poles, it will not set again till about the time of the next equinox, but will go spirally round the sky until it has risen at the solstice about one-fourth of the way to the zenith (298), after which its course round the sky will gradually fall back again towards the horizon, and at length below it.

**322.** The best way to get clear notions of the daily and yearly changes above described, is to watch the stars until their daily courses have become familiar, and until the equatorial and circumpolar stars (284) can easily be distinguished at all times of year, even if the names of the separate stars of each kind are not known. Sufficient observation of this sort will enable any one to learn the apparent yearly course of the Sun among the stars (292); for although the stars among which the Sun would appear to be at any particular time, if they could be seen, are in fact invisible owing to the Sun's brightness, yet we can watch the stars which seem just before sunrise and just after sunset to be nearest to the Sun. In this way we notice that the Sun is always moving towards some of the stars seen after sunset and away from some of the stars seen before sunrise, so that a star which sets on any evening soon after the Sun, and at nearly the same place with it in the horizon, can no longer be seen a few evenings later, and after some time rises just before sunrise nearly where the Sun appears on the same morning shortly afterwards. The stars near which the Sun seems to pass are equatorial, northern, or southern stars (286), according to the time of year at which they are passed. The Sun's course among them is so nearly the same from year to year,

that no change can be noticed in it without very careful observations. This course is the imaginary line called the **ecliptic**. It is in fact a projection of the Earth's orbit on the sky (270).

**323.** The **zodiac** is the name given to a belt or strip of sky without any exact boundaries, but considered as including all the stars near the ecliptic on both sides (277). If we are acquainted with these stars, we can see on any evening through what part of the sky the zodiac then extends. The equatorial stars may be regarded as forming another belt, which, as seen from any one place, always extends over the same part of the sky, forming an arch which meets the eastern and western parts of the horizon (282), and passes north or south of the zenith, according to the situation of the observer south or north of the equator. The stars which form this arch differ with the seasons (292), but the place of the arch remains the same. The zodiac must cross this equatorial belt of stars at the two opposite places where the Sun seems to be when it is an equatorial star; or, in other words, where the Sun seems to be at the time of the equinoxes. These places themselves are often called **equinoxes**, and the parts of the zodiac which are farthest north and south of the equatorial belt of stars are often called **solstices**, because at the time of the solstices the Sun seems to be in those parts of the zodiac. A more precise meaning than this is given in practical astronomy, as will be seen, to the terms equinox and solstice when they are used to denote places; but the explanation just given is best for our present purposes.

**324.** Let us next consider the appearance of the zodiac just after sunset at the time of the vernal equinox. The place of this equinox is now just below the western part of the horizon, and the place of the autumnal equinox just above the eastern part of the horizon. The part of the zodiac in sight is that which the Sun is to traverse during the next half year; it must therefore form an arch from east to west with its summit nearly north of the highest equatorial stars. As seen from any part of the Earth half-way from the equator

to the Tropic of Cancer, the zodiac must now pass about as far north of the zenith as the highest equatorial stars are south of the zenith. To an observer still farther north, the arch formed by the zodiac must seem more nearly upright than the arch formed by the equatorial stars.

**325.** Just after sunset at the time of the summer solstice the autumnal equinox will lie among some of the highest equatorial stars, so that the zodiac will cross the sky from a place north of the western to one south of the eastern part of the horizon. Just after sunset at the time of the autumnal equinox the zodiac will cross the sky from east to west again, but will pass south of the highest equatorial stars, so that to an observer in the north temperate zone, for instance, it will form an arch leaning far towards the southern horizon. Just after sunset, at the time of the winter solstice, it will reach from north of east to south of west.

**326.** The planes of the orbits of the Moon, and of all the planets which are easily visible, differ so little from the plane of the ecliptic that the objects moving in them must always appear to be somewhere in the zodiac. This fact will help us to understand the appearances occasioned by the movements of the Moon and planets, now that the effect of the Sun's movements has been considered.

**327.** Two celestial objects are said to be in **conjunction** with each other when they appear to be near each other in the zodiac; and to be in **opposition** to each other when their places in the zodiac are nearly opposite to each other, so that one of them is half-way from its rising to its setting when the other is half-way from its setting to its rising. One object is in **quadrature** with another when half-way between conjunction and opposition with it. All these terms are used with a more exact meaning in practical astronomy than appears from this explanation, which is sufficient, however, for our present use. When any object is said simply to be in conjunction or opposition, the Sun is understood to be the object with which the conjunction or opposition is made.

**328.** An inferior planet (198) cannot be in opposition to

the Sun, but may come into conjunction with it in two ways: it may pass nearly or exactly between the Sun and Earth, or it may pass nearly or exactly behind the Sun as seen from the Earth. In the first case the conjunction is **inferior**, in the second case **superior** conjunction. When it passes exactly between the Sun and the Earth it must appear as a black spot crossing the Sun's disk. This appearance is called a **transit** of the planet.

**329.** A superior planet (199) can have no inferior conjunction, and the Moon can have no superior conjunction; but the Moon may be in opposition to the Sun, and so may any superior planet. When the Moon passes exactly between some part of the Earth and some part of the Sun, the Sun is **eclipsed**.

**330.** Any object lighted up by the Sun, and either in opposition to it, or in superior conjunction with it, will have its bright side towards the Earth; if in or near inferior conjunction with the Sun, its side seen from the Earth will be wholly or nearly dark. In this way arise the appearances which are called **phases** of the Moon and planets. The Moon is said to be new either when it is in conjunction with the Sun, or as soon afterwards as it can be seen. It then appears as a bright crescent east of the Sun, not giving light enough to be seen until after sunset. A flat disk would be faintly lighted up all over as soon as it was turned at all towards the Sun; so that the appearance of the new moon shows that the Moon is globular, bulging out towards us so as to cut off the sunlight from the parts of its disk at a distance from the preceding limb, which is that now turned towards the Sun. At this time the terminator (194) is shaped like half an ellipse, because it is a projection (270) of the boundary between the light and dark parts of the Moon, and this boundary runs over ground which bulges out towards us. When the Moon is near its quadrature with the Sun, the terminator is nearly straight, because the boundary of which it is a projection is then seen nearly edgewise. This may be illustrated by means of the elliptical and straight

lines, representing circles, which are usually drawn upon maps of the Earth.

**331.** Any globular body has a **gibbous** appearance when seen in such a light that more than half but not the whole of its disk is illuminated. The Moon is accordingly gibbous between its quadratures and its opposition. When near opposition, it is said to be full. The faint illumination of the Moon by the Earth has been noticed above (193).

332. Venus and Mercury, on the other hand, are full only about the times of their superior conjunctions, when they are too nearly in a line with the Sun to be seen. Their phases, or the changes of shape in the illuminated parts of them which can be seen from the Earth, cannot be noticed without telescopes, mainly by reason of irradiation (193.) Some people, however, think they can see at times that Venus is not quite round. When the boundary between the light and dark parts of an inferior planet is turned edgewise to the Earth, it appears as a straight terminator, and the planet's disk, as seen through a telescope, looks like a half moon. About this time the planet seems to be as far away from the Sun in the zodiac as it is to go between its last and next conjunctions. This does not happen half-way between one conjunction and the other, for the same reason for which a ring put edgewise into a funnel touches the sides of the funnel at two places which are nearer together than the full width of the ring. If the ring is supposed to be viewed from the bottom of the tapering part of the funnel, it must seem widest where it touches the funnel instead of where it is really widest (267). In like manner, the orbit of Venus, for instance, looks widest to a terrestrial observer where straight lines drawn to it from his station would just touch it and pass on without crossing it. The places in the planet's orbit touched by these lines seem to the observer to be farthest from the Sun ; and when the planet is at one of these places it is said to be at its greatest elongation east or west of the Sun, as the case may be.

333. Between one of its elongations and its superior con-

junction a planet like Venus or Mercury must appear gibbous. Between either of its elongations and its inferior conjunction it must appear as a crescent. It will look brightest at some time when it appears as a crescent, because its approach to the Earth as it comes towards its inferior conjunction will more than make up for the turning away from us of its bright side, until the crescent which it shows us has become very narrow.

334. The superior planets cannot appear as crescents, or even as half moons, because they have no inferior conjunctions. But near their quadratures with the Sun, Mars looks decidedly gibbous, and Jupiter slightly gibbous. We never get far enough out of the line joining Saturn with the Sun to make it appear even slightly gibbous; and of course, therefore, Uranus and Neptune can show no phases.

335. The time between one new moon and the next, or between one superior conjunction of any planet and the next superior conjunction of the same planet, cannot be the same as the period of revolution of the Moon about the Earth or of the planet about the Sun. For all conjunctions and oppositions depend on the place of the Earth in its orbit as well as on the places of the bodies observed to be in conjunction or opposition. The time from one conjunction to the next conjunction of the same kind, or from one opposition to the next, is called the time of one synodical revolution of the object under consideration. The time of its sidereal revolution is that which it occupies in once traversing the whole projection of its orbit viewed from the place around which it revolves; the ecliptic, for instance, is the projection of the Earth's orbit (322). The time of the anomalistic revolution of a celestial object is that between one of its perihelion passages and the next, or, in the case of a satellite, between two of its successive returns to that part of its orbit where it is nearest to the body around which it moves. The sidereal revolution is what we usually understand by the revolution of one body about another, unless that revolution is expressly stated to be synodical or anomalistic.

336. The Moon keeps the same side to the Earth because the period of its rotation agrees with that of its sidereal revolution (177), but in other respects this sidereal revolution of the Moon is unimportant to us in comparison with its synodical revolution, on which depend, as we have just seen, its changes of appearance. The time of one of the Moon's synodical revolutions is often called a lunation. During every lunation the Moon completes one sidereal revolution and begins another; for its real motion and the Sun's apparent motion among the stars are both direct. Hence, when it arrives at the place in the zodiac from which it started, the Sun has moved some distance beyond its place at the beginning of the Moon's sidereal revolution, so that the Moon has to go farther before it is again situated in the zodiac as it then was with respect to the Sun. One lunation occupies about twenty-nine and a half days.

337. The divisions of time called months were originally meant to agree with lunations; but as there are between twelve and thirteen lunations in a year, and as it was found inconvenient to begin the year except at the beginning of some month, the months finally came to be mere customary divisions of the year, not answering to any astronomical events.

338. The small differences in the apparent movements of the Moon due to the changes of the plane of its orbit, and of its orbit in that plane, produce no effects which need here be considered. We need only inquire how far the appearance of the Moon when it is new or full depends on the place of the zodiac at those times. Let us suppose that it is new moon about the time of the vernal equinox, and that we are placed in the north temperate zone. The arch in the evening sky now formed by the zodiac is more upright than usual (324), so that the Moon is nearly over the place where the Sun has just set. In this case the lower limb of the Moon will be turned to the Sun, so that the horns of the crescent will seem to be more nearly than usual on a level with each other. If the time is that of the autumnal instead of the

vernal equinox, the arch of the zodiac will slant towards the south (325), and the Moon will appear to us so much to the left of the Sun that its crescent will be more nearly upright than usual. At other times of year the crescent will slant more or less towards the horizon according to the place of the zodiac in the sky, and to some extent according to the Moon's place north or south of the ecliptic, in the zodiac; but this makes comparatively little difference in its appearance. The farther we are from the equator, the greater will be the difference in the appearance of the new moon at different times of year. It is curious that the slant of its crescent towards the horizon has been taken by some people for a sign of wet or dry weather. Those who made this blunder must have been careless observers not to notice that like appearances returned in order every year.

**339.** The full moon is seen in the part of the zodiac opposite to the Sun. Accordingly, when the Sun is an equatorial star the full moon is also among the equatorial stars; when the Sun is a southern star the full moon is among the northern stars; and when the Sun is a northern star the full moon is among the southern stars. Hence about the time of the winter solstice the full moon rises far north of east and sets far north of west; and the full moon is longest above the horizon at that time of year when the nights are longest.

340. Although the direct motion of the Moon carries it along the zodiac much more quickly than the Sun is carried along the zodiac by its apparent direct motion, the retrograde motion of the Moon, due to the Earth's rotation, is still quicker; so that we might count days by the Moon, if we chose. These days might be called lunar days, and their lengths might be measured as the length of a sidereal day according to any particular star may be measured (311). That is, if a flat plate is fixed upon the Earth so that it stands upright, with one side facing due east and the other due west, the lunar day may be considered as beginning or ending when the Moon's place above the horizon is opposite the edge of this plate. We might regulate a clock to such a

rate that the number of days in a year according to this clock would be equal to the number of lunar days in the same year. The clock would have to lose about forty-nine minutes a day as compared with an ordinary mean time clock, because the Moon lags more than the Sun, so as to lose about a day of mean time in any single lunation. But it does not follow that the Moon will rise forty-nine minutes later every day than it did the day before. Different lunar days differ in length still more than different solar days; so that the Moon would be found to gain and lose on a clock so regulated as on the whole to keep time with it much more than the Sun gains and loses on mean time clocks. The Moon's speed in its orbit varies during each of its revolutions round the Earth; and the changes of its orbit are quick compared with those of the Earth's orbit. But even if it kept exact time with a suitably regulated clock, the times of its rising and setting would be changeable compared with those of the Sun; for its direct movement may be resolved into others, just as the Sun's direct movement was resolved above (297). Now, since the Moon's whole direct movement along the zodiac is much quicker than the Sun's, its northward and southward movement is sometimes much quicker than the Sun's, while at other times, when the Moon is near a solstice (323), it must come to a pause; so that its speed changes more than the speed of the Sun's northward and southward movement, and this change of speed will make the time of moonrise still more changeable than the time of sunrise (318). The rising of the Moon is seldom noticed except at the time of full moon; for at other times it happens either while the Sun is still above the horizon or late in the night. We will therefore consider only those changes in the time of moonrise which happen at full moon and at places in the north temperate zone.

341. When the Moon is full in spring, it must be near the place of the autumnal equinox in the zodiac; for the Sun is then near the vernal equinox (324). Every evening, then, the Moon is farther south, and must on this account rise later, than the evening before. Accordingly, there is now an

unusually large difference by a mean time clock between one moonrise and the next. In autumn, the Moon is near the vernal equinox when full, and its northward movement, which is at this time unusually quick, greatly lessens the ordinary delay of its rising, which is due to its lagging behind the Sun. Hence any full moons which occur from the latter part of August to the latter part of October will rise for several evenings in succession much more nearly at the same mean time than usual. Full moons of this kind have been called harvest moons when they come about the time of harvest, and hunter's moons when they come in October. From a place far enough north, a harvest moon may be seen to rise earlier than it did the night before, instead of later. In places about half-way from the equator to the north pole, a harvest moon ordinarily rises only about a quarter of an hour later, while a full moon in spring rises about one hour and a quarter later, than on the previous evening. By means of the explanations already given, we might follow out the apparent movements of the Moon at various times of a lunation occurring at any season of the year; but these movements do not require any description in a work of this kind.

342. The apparent movements of Venus and Mercury are by turns direct and retrograde, carrying these planets past the Sun from one elongation to the other (332). An inferior planet has an apparent retrograde movement when passing between the Earth and Sun; that is, its movement from its eastern to its western elongation carries it through its inferior conjunction; while its movement from the west to the east of the Sun carries it through its superior conjunction. When Venus is near its eastern elongation, so as to be visible for a time after sunset, it is usually called the evening star; and when seen in the morning near its western elongation it is called the morning star. At these times it is far brighter than any celestial object except the Sun and Moon, and gives light enough to cast distinct shadows on any smooth white surface. It may often be plainly seen while the Sun is above the horizon. It is brightest, as has been said, a little after

its eastern or a little before its western elongation (333), when it appears as a crescent in the telescope. The horns of this crescent seem extended farther round the disk than they would reach by means of irradiation alone; this extension is thought to be due to refraction in the planet's atmosphere.

343. Within the crescent formed by the illuminated portion of the disk of Venus, the rest of the disk is sometimes visible, like that of the new moon (193). How this happens is not known; for Venus is never near enough to the Earth to get much reflected sunlight from it, as the Moon does. It is possible that some light like that of the terrestrial aurora may at times be shining in the atmosphere of Venus; but this is nothing more than one of the guesses which have been made about the appearance just described, although it is a more likely guess than that of one astronomer, who thought that Venus might be inhabited by people who had a custom of lighting bonfires occasionally all over their planet.

344. The names of morning and evening star are sometimes given to Mercury, and even to some of the superior planets, as well as to Venus; but Mercury is a planet seldom noticed at all, being generally too nearly in a line with the Sun to be visible. When it can be seen, it appears like a rather bright star.

345. The apparent movements of the superior planets along the zodiac are direct, except when the Earth passes nearly between the Sun and one of these planets, so as to bring it into opposition. At such times the planet has an apparent retrograde movement, due to the facts that its real direct movement is slower than that of the Earth, and that the Earth's movement is almost directly across the line joining the planet and the Sun. Any superior planet, about the time of its opposition, will apparently retrograde farther, but will occupy fewer days in retrograding, than will any planet much more distant from the Sun, and therefore from the Earth. Hence Mars, the nearest of the superior planets, has a remarkably unsteady apparent movement; retrograding

rapidly for a comparatively short time, and at other times changing the rate of its direct movement considerably in different parts of the zodiac. These effects are often increased by the considerable eccentricity of its orbit; so that before the discovery of Kepler's laws its movements were thought very perplexing, and could not well be accounted for by any theory of the Solar System that had been contrived.

346. The apparent direct motion of a superior planet cannot ordinarily be as quick as the apparent direct movement of the Sun; so that at the time of the conjunction of the planet the Sun apparently overtakes and passes it. The times of day at which any planet rises and sets during any season depend, of course, on its place at that season in the zodiac; the explanations already given with regard to the Sun and Moon will be sufficient to account for the appearances occasioned by such movements of the planets as can be observed without astronomical instruments.

**347.** The appearances called transits, eclipses, and occultations, still remain to be noticed. These are all due to the passage of one celestial object directly between two others, and may all be illustrated by some such comparison as the following.

**348.** If a man is walking past some large building, at a considerable distance from it, while carriages are occasionally passing between him and the building, they will hide more or less of it from him as they pass, according to their distance from him and their size. A small carriage passing within a few feet of him may hide the whole length of the building for a second or two; while a still larger carriage driven close by the building will appear to cover only a small part of it at once. If a low carriage or an open wagon passes between the observer and the building, he may be able to see the upper part of the building over the carriage, even if it passes near him.

**349.** Any particular carriage, then, will hide more of the building the nearer it passes to the observer. But it will take

longer to pass in front of the building the farther it passes from the observer. Suppose two straight lines drawn from the observer, one to each end of the building. Then a carriage will begin to hide the building as soon as it begins to cross the first of these lines to which it comes, and will continue to hide some part of the building until it has entirely crossed the second line. But the space it has to cross from one line to the other is greater the farther it is from the observer. If it is not driven directly across this space, it will usually be longer between the lines than it would be if it crossed both of them equally far from the observer; but if its course carries it partly towards him, it will come to the second line at a place where the two lines are nearer together than they were at the place where it crossed the first line; so that its course between the lines may be no longer, or may even be shorter than if it had crossed them both equally far from the observer.

**350.** If the observer, as we supposed at first, is himself moving along while the carriage passes, the two lines will be always shifting their places. This will make a difference in the particular time at which the carriage will cross either of them; but it will not make any difference in the two general rules that the carriage hides more of the building at a time the nearer it is to the observer, and continues to hide one part or another of the building for a longer time the farther it is from the observer. Of course, if the carriage and the observer are moving contrary ways, it will not be so long between him and the building as it would be if it moved the same way with him.

**351.** There is another way of looking at the same facts. Suppose it to be evening and that the building is illuminated. We may wish to inquire how much ground will be covered by the shadow of the carriage. In order to distinguish between the ends of the building, we will call them north and south ends, considering the building as facing eastwards. Then if a line is drawn from the northernmost light in the building past the northern edge of the carriage, and from the

southernmost light in the building past the southern edge of the carriage, the place where these lines cross, beyond the carriage, will be as far as its shadow reaches. Anywhere between these lines, and between the place where they cross and the carriage, the carriage cuts off the view of both the northernmost and the southernmost light at once. Outside of this space, one light at least will not be behind the carriage.

**352.** But if we wish to know the shape of the space from which the carriage hides *some* of the lights in the building, we may suppose lines drawn from all the lights near the ends and top of the building, so that each line touches the carriage on the edge farthest from the light it starts from. For instance, let a line be drawn from the northernmost light to the southern edge of the carriage and from the southernmost light to the northern edge of the carriage. These lines will cross or come nearest to each other between the building and the carriage, and will get continually farther apart beyond the carriage; so that the farther off we are the more space there will be within which some of the light from the building is cut off by the carriage.

**353.** When a dark object, like the Moon or a planet, is considered as lighted up by the Sun on one side and casting a shadow on the other, the shadow itself is called an **umbra**, and the space behind the planet from which it cuts off some sunlight is called a **penumbra**. In this sense, the words umbra and penumbra have a very different meaning from that which they have when used with regard to the solar spots (56).

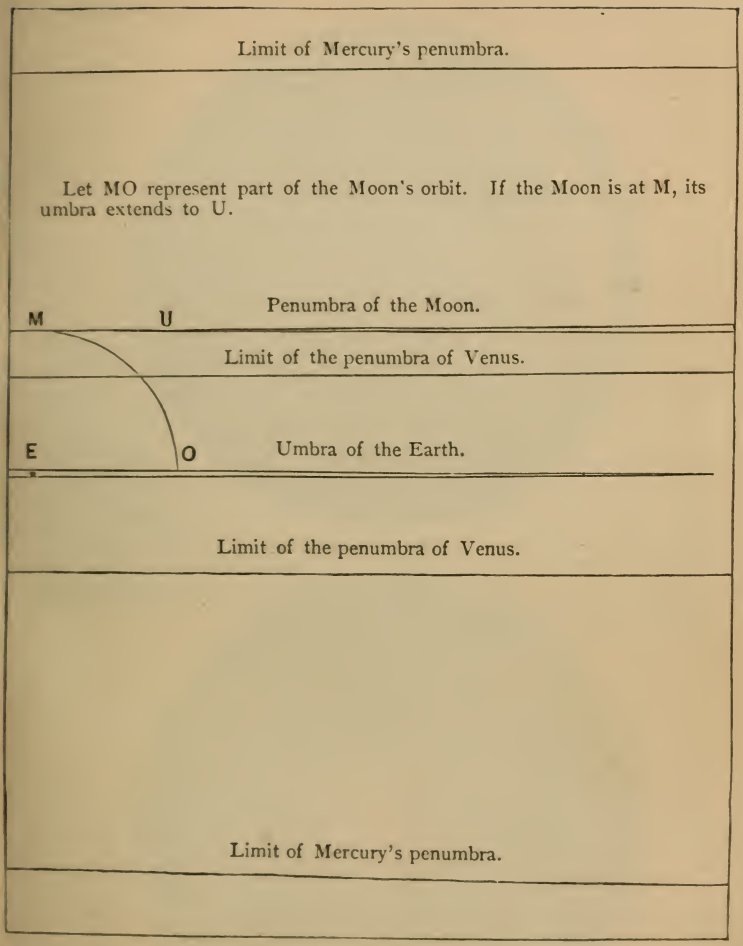
**354.** Since the planets are smaller than the Sun, and are globular, their umbræ are funnel-shaped. From the place where an umbra ends, the planet to which it belongs must look just as large as the Sun; from any place within the umbra the planet must look larger than the Sun; and from any place beyond the end of the umbra the Sun must look larger than the planet (267). If we take a glass funnel and fit two round flat pieces of pasteboard into it, one larger than

## EXPLANATION OF PLATE IX.

In this plate, the dot at E represents the Earth on about the same scale as that on which the Sun is represented in Plate I., page 38. The width of the Earth's orbit, on the same scale, is about equal to the joint length of a number of lines of print, one from each page between Plates I. and IX. By taking one line from each leaf only, we shall accordingly have the distance of the Earth from the Sun. The corresponding extent of the penumbræ of Mercury and Venus, at the distance of the Earth from the Sun, is also shown in Plate IX.

ERRATA. — Owing to an error in the printing of this edition, Plates IX., X., XI., and XII have been placed between pages 193 and 194, instead of between pages 207 and 208. The number of pages between Plates I. and IX. should be about 170, in order to make the explanation of Plate IX. correct.

# PLATE IX.


Limit of Mercury's penumbra.
Let MO represent part of the Moon's orbit. If the Moon is at M, its umbra extends to U.
M
U
Penumbra of the Moon.
Limit of the penumbra of Venus.
E
O
Umbra of the Earth.
Limit of the penumbra of Venus.
Limit of Mercury's penumbra.

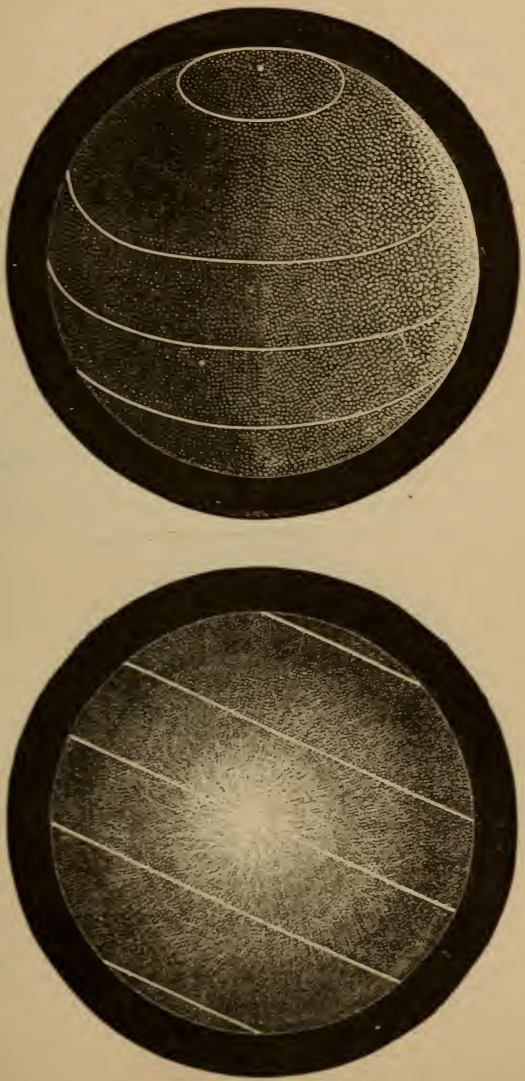
## EXPLANATION OF PLATE X.

The figures of Plate X. show orthographic projections (270) of the Tropics and Polar Circles, and may be compared with the projections shown in Plate XI. Why is the spot marking the place of the pole, in the upper figure, out of the centre of the ellipse representing the Arctic or Antarctic Circle? If we regard this pole as the south pole, is it the time of sunrise or of sunset in that part of the Earth which occupies the centre of the upper figure? In the lower figure, if we suppose Norway to be at the top, is it sunrise or sunset there? On the same supposition, what part of the Earth at this time has the Sun in its zenith? and what is the season of the year, spring or autumn?

# PLATE X.

## DISTRIBUTION OF LIGHT AT AN EQUINOX.

See Sections 270, 293, 299.



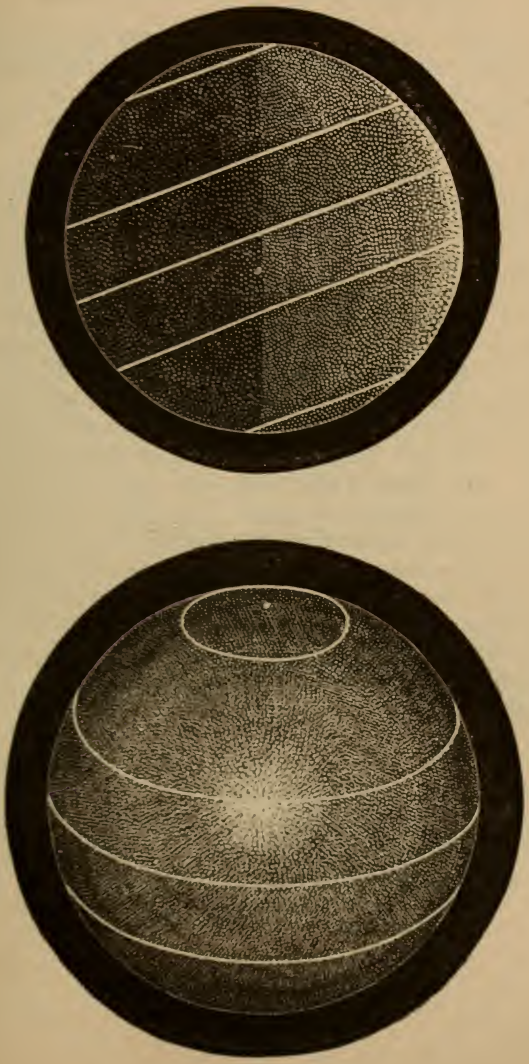
## EXPLANATION OF PLATE XI.

The figures of Plate XI., like those of Plate X., show orthographic projections of the Tropics and Polar Circles. Numerous questions, like those given with Plate X., may be asked with regard to this Plate, and answered with the aid of an atlas.

# PLATE XI.

## DISTRIBUTION OF LIGHT AT A SOLSTICE.

See Sections 270, 295, 299.



## EXPLANATION OF PLATE XII.

The parallel lines shown in Plate XII. may be supposed to lie on a rounded surface, so that they are not all in one plane. The two lines AC and BD, at right angles with each other, are perpendicular to each other, whether we hold one of them vertical, or not.

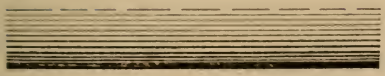
The circle AGDBEH may be understood to represent the intersection of a sphere with the plane of the paper. The sphere has its centre at C in the plane of the paper, and is orthographically projected on that plane (270), the point of sight being indefinitely distant, and in a line drawn through C perpendicular to the plane of the paper. Hence AGDBEH is a great circle of the sphere, and appears as a circle. Any other great circle must appear as an ellipse or straight line. The line AB may be regarded as a diameter of the sphere, or as the projection of a great circle the plane of which is perpendicular to the plane of the paper. The half ellipse APFLB will represent half a great circle. The circles TMN, PQR, are small circles in planes parallel to the plane of the paper. The ellipse RSQ represents a small circle the plane of which is inclined to that of the paper; and GTFH, which is more than half an ellipse, represents part of a small circle, since its major axis does not pass through C. A line drawn from the middle of its major axis through C would be perpendicular to its major axis. If this were not the case, would the ellipse represent a circle of the sphere? Are both ADL and AGF spherical triangles? To what curve is the straight line AB tangent?

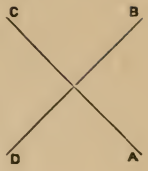
In each of the two cones, the line AB is the axis of the rotation by which the cone is formed, and CD the rotating line. The shape, though not the kind, of any conic section, will obviously vary according to the angle between AB and CD, as well as with the angle between AB and the intersecting plane.

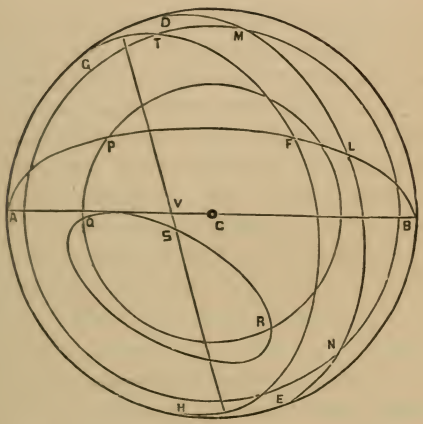
# PLATE XII.

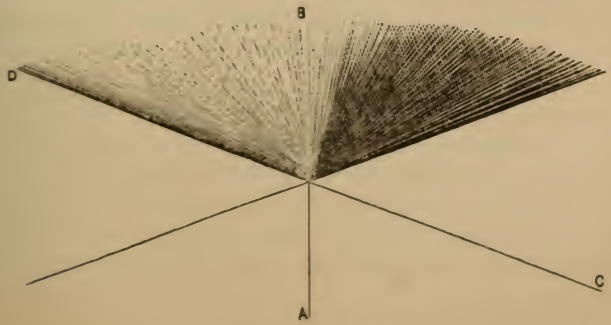
## GEOMETRICAL FIGURES.

See Sections 396, 402, 412, 414, 418, 422.







the other, and nearer the mouth of the funnel, the two pieces must look equally large from the place where the sides of the funnel come together; for the smaller piece would appear from that place just to hide the larger piece; and that place would be the end of the shadow of the smaller piece of pasteboard if the larger piece were luminous.

**355.** The penumbra of a planet takes in more and more space the farther it reaches; and the farther away from the planet is the place in this penumbra from which we may suppose ourselves to be looking, the smaller the planet must look compared with the Sun; although both the Sun and the planet must look smaller than from a place nearer to them.

356. Mercury is a little larger than the Moon (195); but the Moon looks about as large as the Sun, while Mercury has only a small disk when examined with a telescope. Hence, when the Moon comes between us and the Sun, its umbra reaches about as far as the Earth; and it may hide the Sun for a few minutes at a time, while Mercury looks like a small black spot when it is seen upon the Sun's disk. On the other hand, the penumbra of Mercury, where we cross it, has spread out far enough to take in a row of many more than a hundred such bodies as the Earth; while the width of the Moon's penumbra, where we cross it, is only about half the length of the Earth's diameter. Accordingly, when Mercury can be seen on the Sun's disk from any part of the Earth, it will be seen there from all parts of the Earth where the Sun is then above the horizon, unless the Earth is just grazing the penumbra of Mercury. But when the Earth crosses the Moon's penumbra, there will still be terrestrial places from which the full disk of the Sun will be visible. That is, although the Moon is large enough to cover the whole Sun at certain times, yet if we could travel about quickly enough on the Earth, we could apparently shift the Moon from one side of the Sun to the other by our own movements, at times when its centre was nearly between those of the Sun and the Earth. But when Mercury is between us and the Sun, the most that we could do by

moving about on the Earth would be very slightly to shift the place of the planet on the Sun's disk. Still another statement of the same facts would be that the parallax of the Moon, as compared with the Sun's parallax, is larger than the parallax of Mercury as compared with that of the Sun. As the appearances due to parallax are very familiar, the word may be partly explained without the use of mathematical terms.

357. If we look through a window at distant objects, we see that the place of the bars of the window-frame can be made to change considerably, with regard to the objects behind them, by small movements of our own. But we must walk a long way before we can thus change the apparent place of a distant house with respect to the landscape behind it. An apparent change of place of this kind may be called the parallax of the object observed as compared with the parallax of the objects behind it; for these objects must also be slightly displaced, by our movements, with respect to other objects still farther from us. Since the amount of the parallax of an object depends in some way on its distance from us, we may naturally suppose that its distance can be found out by means of its parallax; and this is actually the case. But as no measurements of parallax can be perfectly exact, the distance of a remote object is not easily found. Mistakes in the measurement of its parallax will occasion a greater uncertainty as to its distance than will be occasioned with respect to the distance of a near object by mistakes equally large in the observations made upon it. So far as the distance of any objects beyond the Solar System has been determined, the determination depends upon apparent movements of these objects due to the Earth's motion in its orbit. The mean distances of the planets (147), and hence our distance from the Sun, are learned by observing the parallax of any one planet as compared with that of stars nearly in a line with it, or with that of the Sun. This parallax does not depend on the Earth's movement in its orbit, but only on the different views of the planets which we have from different parts of the Earth.

358. When the actual distance from the Earth of any planet at any particular time has been learned, the mean distances of all the planets may be learned by observing the periods of their revolutions about the Sun; for these periods are connected with the comparative distances of the planets by Kepler's third law (150); or, more strictly speaking, by the general laws of motion. The Moon's parallax, and therefore its distance, can be more easily determined than those of any other celestial object; and one way of determining the distances of the Sun and other objects belonging to the Solar System consists in calculations depending on the Moon's distance and movements; but more direct and satisfactory methods of finding the Sun's distance are furnished by observations of Venus and Mars. At the time of its inferior conjunction (328), Venus comes nearer to the Earth than any other of the principal planets ever does. If it can then be seen, its parallax can be better determined than that of any other planet; but this happens only at those inferior conjunctions when it is so close to the plane of the ecliptic that the Earth enters its penumbra. Transits of Venus (328) are seldom seen, but usually occur in pairs, the time between the two transits of each pair being only eight years. The years of the eighteenth century marked by transits of Venus were 1761 and 1769: those of this century are 1874 and 1882; the next transits will not occur till the years 2004 and 2012.

359. Mars, at its oppositions, comes near enough to the Earth to make observations of its parallax practicable; and our knowledge of the distances among the bodies of the Solar System depends to a great extent on the numerous observations which have been made upon Mars, especially at those oppositions when Mars and the Earth are unusually near each other (200).

360. The transits of Mercury are much more frequent than those of Venus; but Mercury is too far from us to allow its parallax to be very accurately determined by direct observation.

361. The passage of any object across another, or across

a boundary of any kind, may be called a transit; and many astronomical events of very different kinds are in fact called transits. The only transits, except those of Venus and Mercury across the Sun's disk, which we need consider at present, are those of satellites across the disks of the planets to which they belong. The frequency of the transits of Jupiter's satellites has already been mentioned (207). The passage of the shadow of any satellite of Jupiter across the planet's disk is often called a transit of the shadow; it is an event of the same kind with those called eclipses of the Sun, which are due to the Moon's shadow upon the Earth.

362. An occultation is the hiding of an apparently small body behind some other moving object. Jupiter's satellites are frequently occulted by Jupiter; stars and planets are often occulted by the Moon, and sometimes by planets. The occultation of any celestial object behind the Sun could not be observed, as we should lose sight of the object while it was still apparently at a considerable distance from the Sun. Occultations of stars by the Moon can seldom be observed without the help of some instrument; but many can be distinctly seen with a spy-glass or an opera-glass. The disappearance of the star behind the Moon is called its immersion, and its reappearance is called its emersion. Immersions take place on the following limb of the Moon (49, 183), and therefore, from new moon to full moon, on the dark limb. When the dark limb is too feebly lighted to be visible at all, the stars over which it passes seem, at their immersions, to be extinguished without any obvious reason and with surprising suddenness. Emersions from behind the Moon's dark limb may be seen after the time of full moon; but the moment when the star is to appear has first to be calculated, or we do not know when to look for its emersion. Immersions and emersions on the bright limb are less interesting than those on the dark limb. At their immersions on the bright limb, stars occasionally seem to come a little within the limb before they disappear. This appearance is probably due to some optical illusion not yet clearly explained.

363. The Moon is so much displaced among the stars by the effect of parallax that a star seen, for example, a little south of the Moon, near the equator, must appear north of it in the north frigid zone. Hence a star occulted by the Moon at one terrestrial place may escape occultation at another not very remote from it.

**364.** A satellite is said to be **eclipsed** when it is in the umbra of the planet to which it belongs; and the Sun is said to be eclipsed when its light is partly or wholly cut off from us by the Moon. Eclipses of the satellites of Jupiter are very frequent; in fact, the first, second, and third of these satellites (208) are eclipsed every time they go round the planet. The fourth satellite, also, is usually eclipsed at each revolution; but it sometimes passes clear of the planet's umbra, although the extent of this umbra must be nearly as great at the distance of the fourth satellite as it is at any place, on account of Jupiter's great size and distance from the Sun. But the orbit of the fourth satellite does not lie quite as nearly in the plane of Jupiter's orbit as do those of the other satellites.

**365.** When Jupiter is in opposition, its shadow and the shadows of its satellites point nearly away from the Earth. In this case, the satellites must go nearly behind the planet, as seen from the Earth, whenever they are eclipsed; and any satellite which casts a shadow on Jupiter must itself be nearly between Jupiter and the Earth. But this is not the case when Jupiter is at one of its quadratures. Suppose, for example, that Jupiter is high in the sky at sunset. Then its shadow and those of its satellites must be cast eastwards with respect to the terrestrial place of observation; so that a satellite the shadow of which is on Jupiter will be a little west of the planet; and an eclipsed satellite will be a little east of Jupiter, so that its reappearance after the eclipse can be observed, even if its disappearance took place behind the planet. But it often happens that both the disappearance and the reappearance of a satellite of Jupiter may be observed.

366. The shadow of Saturn's ring on the ball or of the ball on the ring constitutes what may be called an eclipse. But the changes of these appearances are too slow to make them like eclipses in the ordinary sense of the word. The eclipses occasioned by the movements of Saturn's satellites occur comparatively seldom, owing to the considerable inclination of the orbits of these satellites to the plane of Saturn's orbit.

**367.** The Moon is not eclipsed very often; for, owing to the inclination of its orbit, it is often out of the plane of the ecliptic when it comes into opposition, so that it passes on one side or the other of the Earth's umbra, which is of course much smaller than Jupiter's umbra, though large compared with the Moon, so that the Moon may continue wholly eclipsed for about two hours at a time, while it is passing through the umbra of the Earth. The Moon is sometimes only partially eclipsed; that is, some part of its disk is near enough to the plane of the ecliptic to be eclipsed at one of its oppositions while the rest of the disk passes outside of the Earth's umbra. When the whole disk of the Moon is eclipsed, the eclipse is total, or is in its total phase. Before and after the total phase, there must of course be partial phases of the eclipse as the Moon gradually enters and leaves the shadow.

**368.** Even when the Moon is farthest within the shadow of the Earth, its disk is still visible; for one of the effects of refraction occasioned by the Earth's atmosphere (262) is to send a little sunlight into some parts of the region from which a direct view of the Sun is cut off by the Earth. Refraction not only turns light out of its course, but separates it into light of different colors; and the middle of that part of the Earth's umbra crossed by the Moon contains a little reddish light, the color of which is due partly to refraction and partly to absorption. Hence the disk of the eclipsed Moon usually appears a dull red. The colors of the Sun and Moon seen near the horizon, and not eclipsed, are due to absorption (265).

**369.** One effect of refraction is to increase the indistinct-

ness of the boundaries of the Earth's shadow, so that it is hard to tell when the Moon first touches this shadow at the beginning or leaves it at the close of an eclipse.

**370.** When the Moon is within the penumbra, but not within the umbra of the Earth, some light is cut off from it, but not enough to darken it so much that it can then be considered as eclipsed. But from any part of the Earth which is within the Moon's penumbra, the disk of the Sun is not wholly visible, some part of it being behind the Moon ; and thus what is called a partial eclipse of the Sun takes place. Eclipses of the Sun, then, must be more frequent than eclipses of the Moon ; for an eclipse of the Moon is not considered as occurring unless the Moon touches the Earth's umbra, while an eclipse of the Sun is considered as occurring whenever the Moon's penumbra touches the Earth. There must be at least two, and there may be five, eclipses of the Sun in the course of a year ; while there may be no eclipses of the Moon in the course of a year, and cannot be more than three. Seven eclipses, five of the Sun and two of the Moon, or four of the Sun and three of the Moon, are as many as can happen in the course of a year. But we see more eclipses of the Moon than of the Sun from any one terrestrial place ; for an eclipse of the Moon must be visible from any place on the Earth from which the Moon can be seen at all ; but the Sun may be eclipsed at one place while its whole disk can be seen from another (356). The various periodical movements of the Moon and of the Earth bring them at every moment into nearly the same situation with respect to each other and to the Sun which they occupied about eighteen years, or more exactly, two hundred and twenty-three lunations, before. Hence the eclipses which occur during every two hundred and twenty-three lunations occur in a like order with those of the two hundred and twenty-three previous lunations, but differ from them to some extent in their appearance.

**371.** An eclipse of the Sun is **central** at any place across the line between which and the centre of the Sun the Moon's

centre is passing. An eclipse of the Sun which is nearly central is total, or is in its total phase, if the umbra of the Moon reaches the Earth, in which case the Moon cannot look smaller and may look larger than the Sun (354) as seen from the place where the eclipse is observed; so that the whole disk of the Sun will be hidden. But if the Moon is near apogee (177) at the time of the eclipse, its umbra will not reach as far as the Earth, and it will look smaller than the Sun. Hence the limb of the Sun will be seen all round the disk of the Moon at places where the eclipse is nearly central, and the eclipse will be annular, or in its **annular** phase. When an eclipse of the Sun is not nearly enough central to be either total or annular, it is called partial, or said to be in a partial phase at any particular time and place. The greatest time which the total phase of any eclipse of the Sun may last at any particular terrestrial place is near eight minutes; but this can only happen when the Earth is near aphelion, so that the Sun looks about as small as it ever does, the Moon near perigee, so that it looks about as large as it ever does, and the place of observation on the equator, where the Earth's rotation helps as much as possible to prolong the eclipse. A total eclipse, along the line where it is central, seldom lasts longer than five minutes in any one place; and its length varies a good deal at different parts of the line where it is central. Since all parts of the Earth are not equally distant from the Moon, an eclipse may be total at one place on this central line and yet appear as an annular eclipse when it passes another place farther from the Moon. The place on the Earth nearest the Moon at any particular time is of course that through the zenith of which the Moon is then passing. At the time of an eclipse of the Sun, the terrestrial place nearest the Moon is also nearest the Sun; but the Sun is too far off for its apparent size to be changed as much as is that of the Moon by a change of the place of observation from one part of the Earth to another. Some people fancy that both the Moon and Sun look larger when they are near the horizon than when they are high in the sky.

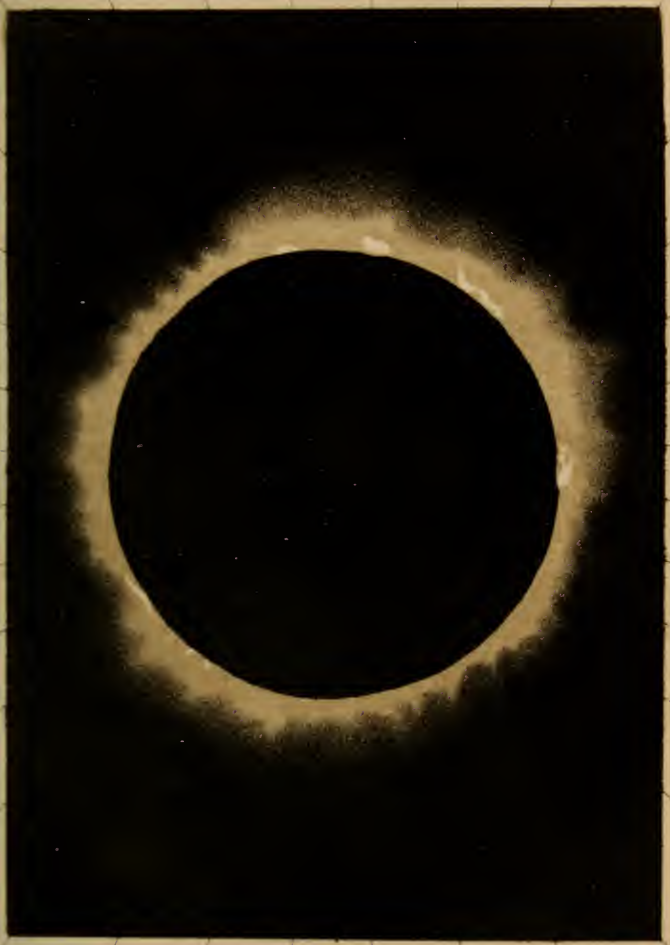
This mistake comes from the fact that when the Sun or the Moon is near the horizon it can be better compared with distant terrestrial objects than when it is high in the sky. In fact, the Sun looks about as large at one height as at another, and the Moon looks largest when it is highest. But the apparent size of the Sun and of the Moon varies noticeably according to the variation of the distances between them and the Earth. The greatest magnitude of an eclipse either of the Sun or Moon was formerly stated by dividing the disk of the eclipsed object into twelve parts, called digits, and naming the number of digits eclipsed; but it is now usual to state the eclipsed fraction of the disk more precisely than can thus be done.

**372.** Even when the Moon is nearest to the Earth at the time of a total eclipse of the Sun, its umbra is reduced to a width of less than two hundred miles before it reaches the Earth. Hence the Sun cannot be totally eclipsed over the whole at once of a very large terrestrial region; and the entire track of a total eclipse of the Sun usually covers only a small fraction of the Earth. Since a large part of the Earth is covered by water, and much of the land is uninhabited, it is not surprising that a total eclipse of the Sun is seldom witnessed.

**373.** When the Sun is totally eclipsed, the corona (73) and any large prominences (67, 69) which may then be on the limb of the Sun can be seen without the help of any instrument. The form, brightness, color, and apparent size of the corona have been very differently described by different observers, so that we can hardly say as yet how the corona usually looks, and cannot say at all why it looks as it does. The total phase of an eclipse of the Sun lasts so short a time at any place, and presents so many strange and interesting appearances, that the spectators of it can hardly notice any thing distinctly before it is over. But accurate observers, each attending only to one appearance, and neglecting all the others, have succeeded, after all, in obtaining much more information during the total phases of recent eclipses than would have been expected.

TOTAL ECLIPSE OF THE SUN AUG 7th 1869

*Plate VIII.*



This view is copied from a photograph. It shows the corona and prominences. The apparent indentations on the Moon's limb under the prominences are due to the prolonged exposure of the photographic plate which was necessary to secure a view of the corona.

374. During a total eclipse of the Sun, the darkness is about as great as it is a few minutes after sunset; and the arrangement of the clouds in the sky at the time makes much difference in the amount of the darkness when the Sun is concealed, either by the Moon, or by the Earth itself just after sunset. Several of the brightest stars and planets may usually be seen while the Sun is totally eclipsed. The Moon itself is faintly illuminated at such times by sunlight reflected from the parts of the Earth outside of the Moon's shadow; and it has been thought that the different tints which the Moon has seemed to have at the times of different eclipses may be due to the differences which there must be between the light reflected from one part of the Earth and from another. When the Pacific Ocean, for instance, faces the Sun and Moon, the Moon's color may be expected to differ from that which it will have when illuminated by light reflected from the continent of Asia. The Moon looks globular to some observers when seen against the coronal light; this may be due to the effects of light and shade produced on it by reflected light from the Earth.

375. The light by which terrestrial objects are seen during a total eclipse of the Sun is generally reported to be somewhat unlike ordinary twilight. This may naturally be the case, since the effects of refraction, absorption, and reflection, to which this light is due, must usually differ from those which produce twilight. Animals are sometimes frightened by a total eclipse of the Sun, but more commonly act as though they supposed the Sun to have set in the usual way. Poultry, for example, go to roost, and cattle return to their stables. The daylight seems gradually to diminish before the total phase of an eclipse of the Sun; but the instant the Sun begins to reappear, the full brightness of daylight seems to return. In like manner, we notice the gradual lessening of the daylight before sunset, but not its increase after sunrise.

376. Just before and after the total phase of an eclipse, the Moon's shadow may sometimes be noticed sweeping rap-

idly over the landscape; and singular wavy lines of light and shade appear upon the ground, the cause of which has not been determined.

377. While an eclipse of the Sun is in its partial phase, the part of the Sun's disk not yet hidden appears as a crescent of greater or less width. When the crescent is very narrow, just before or after the total phase of the eclipse, it often appears to be broken up into detached portions. This effect is considered to be due to the unevenness of the Moon's limb, and to be increased by irradiation. The appearance goes by the name of Baily's Beads, Baily being the name of an astronomer who called attention to this breaking up of the Sun's limb.

378. A few extracts may here be given from the numerous reports made upon the total eclipse visible in the central parts of the United States on August 7, 1869.

379. At Shelbyville, Kentucky, according to Mr. Blake, "about twenty-eight minutes before totality . . . I noticed that shadows were quite indistinct; that the air was growing chilly; and that the sunlight gave a peculiarly gloomy aspect to the landscape.

380. "Thirteen minutes before totality the air felt quite cold; the Sun appeared as a beautiful crescent, while the black edge of the Moon seemed to stand out from it, giving one the idea of a stereoscopic picture. . . . I was struck by the appearance of the trees to the eastward of the tent, and about fifty feet distant; the foliage was of a peculiar color, very similar to that produced by the electric light. . . .

381. "Eight minutes before totality, the limbs of the Sun and Moon were shaking violently, and the sunlight was diminished to such an extent that the faces of the observers were of a livid hue, not unlike that of a corpse. Facing to the eastward, I saw that the southern edge of my shadow was comparatively sharp and distinct, while the northern edge was ill-defined and very faint. . . .

382. "The corona, of which, up to this moment" (that of the beginning of the total phase) "there had been positively

no indications, now appeared as an extremely soft white light, surrounding the Sun and extending from it, in all directions, to a distance of at least two-thirds of its diameter. There was no appearance of rays, nor was there any sparkling light. . . .

383. "Simultaneously with the appearance of the corona, some of the planets and larger fixed stars became visible to the naked eye. They did not appear as they ordinarily do at night, but seemed to shine with a very soft and slightly diffused white light. The sky, in the vicinity of the Sun, was not blue, as at night, but was of a peculiar milky hue; in the zenith it seemed to be of a purplish tinge, and had a more gloomy aspect; the eastern sky was lighted up with a lurid glare similar to that which sometimes attends an autumn sunset. . . . The darkness was so great that it was impossible to distinguish the foliage of trees a few rods distant."

384. General Myer saw the eclipse from the summit of White Top Mountain, in Virginia. According to his account of the appearances noticed during the total phase, —

"As a centre stood the full and intensely black disk of the Moon, surrounded by the aureola of a soft bright light, through which shot out as if from the circumference of the Moon straight massive silvery rays, seeming distinct and separate from each other, to a distance of two or three diameters of the lunar disk; the whole spectacle showing as upon a background of diffused rose-colored light. This light was most intense and extended furthest at about the centre of the lower limb, the position of the southern prominence. The silvery rays were longest and most prominent at four points of the circumference, two upon the upper and two upon the lower portion. . . . These discrete rays were not visible to me, or did not attract my attention, with the telescope, and the diffused rose-colored light seemed to resolve itself in the field of the glass into the prominences. . . . The sight presented to the unaided eye was the superior in beauty; that through the glass in interest. This was so markedly the case that there was a

sense of disappointment, on resorting to the telescope, at finding the size and beauty of the spectacle, as seen by the naked eye, so much reduced by the definition of the glass.

385. "The approach of the Moon's shadow did not appear to be marked by any defined line, or movement of any dark column of shade through the air. The darkness fell gradually, shrouding the mountain ranges and the dim world below in most impressive gloom. Our guides had been instructed to watch for the shadow as described, and to call to us at the glasses. They saw nothing of which to give notice. At the same time, and in vivid contrast, the clouds above the horizon were illuminated with a soft radiance; those towards the east with lights like those of a coming dawn, orange and rose prevailing; those northward and westward, as described to us by Mr. Charles Coale, of Abingdon, Virginia, who was present, with rainbow bands of light of varied hues."

386. Mr. Coale's account of this appearance is as follows: —

"Those who have had the privilege of being upon White Top, and enjoying the westward scene, will remember the grand panoramic view of mountains beginning on the northern and southern horizon, and stretching away to the west till they seem to meet. . . . Stretching along this semicircle of mountains, in long horizontal lines, far below the Sun, lay light and fleecy clouds. . . . At the moment of the falling of the dark shadow, when naught was to be seen above but the stars and the circle of light around the Moon, these clouds became arrayed in all the colors of the rainbow."

387. In a letter afterwards written, Mr. Coale says with reference to the preceding description: —

"I distinctly remember that there were distinct bands of pink, purple, yellow, orange, and fiery red, and each slightly tinged with different shades of its own color. One of the bands, I remember, had to my vision a slight lilac tinge. I do not remember to have observed any green or blue, but

I do remember that the lower edge of the purple had a very faint blue tinge."

388. From the preceding accounts we may readily perceive that, when seen under favorable circumstances, the total phase of an eclipse of the Sun presents appearances like those of a fine sunset or sunrise, in addition to the peculiarly interesting spectacles afforded by the dark disk of the Moon surrounded by the light of the Sun's corona, and by the character of the light scattered through the atmosphere around the spectator (375). General Myer's remark, that the use of a telescope lessened the beauty of the appearances seen without one, is generally applicable to astronomical appearances, almost without exception. Telescopes are useful means of acquiring knowledge, when used by persons who understand how to use them to good advantage; but they add little or nothing to the grandeur and beauty of the sky and the stars. Those who imagine that wonderful sights are constantly to be enjoyed by means of astronomical instruments, fail to comprehend what those instruments are made for. To explain this will be one of the chief objects of the following chapters.

## CHAPTER VIII.

### GEOMETRICAL TERMS.

389. OUR attention has thus far been mainly directed to various opinions respecting the objects which make up the universe, many of these opinions being firmly established, while others are still under examination by astronomers. To understand how any of them have been formed, we must know something of geometry, of optics, and of the technical terms used in practical astronomy.

390. The object of geometry is the measurement of material objects, or the study of their sizes and shapes. It makes no difference in the geometrical study of any object whether this object is a solid, a liquid, or a gas ; whichever it is, it may be called a geometrical solid. The weight, color, and chemical properties of all objects are also left out of sight when the objects are regarded as geometrical solids. A geometrical solid, then, is whatever takes up any space ; any part of space, in fact, may be called a geometrical solid, even if it contains no matter.

391. Now if a geometrical solid is cut in two, there is something belonging at once to both of its parts which has shape and size, and yet which does not add any thing to the size of those parts ; for they are no larger, when taken together, than the solid from which they were made. This something is called a **surface**. We are sometimes reminded that the finest statues ever made were already in the blocks of marble from which they were cut, before their sculptors began to make them. In other words, all that is important about a statue is its surface ; nobody can make a new material object, but a new surface can easily be made, although it is not easy to make one that is beautiful. The space round any material object may be considered as part of a geometrical solid of

which the object itself is another part. The surface of the object is the partition between these parts. We have seen that every plane may be regarded as a partition dividing the universe into two parts (137); and a plane is one kind of surface.

392. A surface, then, is whatever may be regarded as dividing a geometrical solid into parts, without being itself a geometrical solid. But a surface, like a solid, may be cut into parts, and the boundaries between these parts are called **lines**. So, too, a line may be cut into parts; and these parts are marked off from each other by **points**. A point cannot be divided into parts; that is, it has no size of any kind; it is only the end of a line, or of part of a line. Any surface, line, or point, is said to be common to the two solids, surfaces, or lines, which it marks off from each other.

393. Whenever a body moves, any point which we may please to imagine in it goes along some line; so that, although no number of points could be put together so as to make a line, no matter how short, yet no point can move without going through the whole of some line. This is a sort of puzzle, or paradox, as it is called, the explanation of which does not belong to mathematics. Mathematicians, however, have to contrive some way of suiting their reasonings to the facts of nature, and they usually do it by considering every moving object as first in one place, then in another close to it, and so on, without attending to the passage of the object from one place to the next. The places can be supposed to be as close together as is required by the nature of the subject to which any mathematical reasoning may be applied. In this way a line may be regarded as a string of points.

394. When a point is regarded as part of a moving body, it is said to **describe** the line along which it is carried. In like manner, a surface may be described by a line, and a solid by a surface. Some lines and surfaces, however, may be so moved as to describe nothing beyond themselves. Surfaces, lines, and points, may of course be considered as moving,

even when we do not take the trouble to suppose a moving solid to which the moving surface, line, or point, belongs (137). Any number of geometrical solids, surfaces, lines, or points may be considered as occupying the same place. When two of them occupy exactly the same place, they are said to **coincide**; and even if they do not coincide at the time when they are considered, they are said to be **equal** if they might be made to coincide without altering the shape of either. If they are not equal, and yet might be made to coincide if one of them were first cut into parts and the parts all put together again in a new way, they are said to be **equivalent.**

395 A solid may move so that the line described by each of its points, or, in other words, by each of the points we please to consider as belonging to it, shall be equal to the line described by every other one of its points, during any particular part of the movement. We can suppose a movement of this kind to have been going on and to keep on as long as we please, so that the lines described in it have no known beginning or end. Let us take a part of one of the lines thus described, and move it so that all its points may describe equal lines in any given time, and so that it may touch others of the original set of lines. If it always coincides with some part of whichever of these lines it touches, as soon as it touches it at all, then all the original lines must be what are called **straight** lines, and the original movement must have been of a kind called **rectilinear.** This explanation of straightness may seem less comprehensible than straightness itself, the meaning of which is seldom doubtful. However, the straightness of material objects is actually tested by applying them to each other in different ways. The word straight is frequently omitted in speaking and writing; when a line is mentioned, unless we are given to understand that it is not straight, we presume it to be a straight line.

396. The straight lines described by the points of a body which has rectilinear motion are all said to be **parallel** to

each other. All these lines are said to have the direction of the movement by which they were described. A body may be imagined so large as to extend as far every way as we please; and if such a body has a rectilinear movement, its points will describe a set of parallel straight lines occupying all imaginable places. The rectilinear movements considered in geometry are mainly of this kind; it is to be understood that every straight line is as long as we please to suppose, so as to have no beginning or end (395), and that every point we can name is one of the points belonging to some straight line parallel to the first, and having the same direction with it; unless we see by what is said about the line we are considering that it is only part of a line. Even then, a line parallel to it can be drawn through any point we choose.

397. Now, as a matter of fact, no point can be in more than one direction from another; and if any two lines are parallel, each is parallel to any line parallel to the other. If the same set of parallel straight lines is described by each of two rectilinear movements, and the parts of each line are not described in the same order in the two movements, although each part is described but once in each movement, the directions of these movements are opposite.

398. A **direction**, then, is that in which a rectilinear movement, extending through all parts of space which we please to imagine, differs from every other such movement which does not describe the same set of parallel straight lines, and describe the parts of each line in the same order.

399. The notion of direction is commonly taken to be so simple that straightness may be explained by means of direction. However, to say that a straight line is one everywhere having the same direction only amounts to saying that a straight line is everywhere straight; and it may be said that a line is still straight if we please to consider the direction of one part of it contrary to that of another. But this would be only a quibble.

400. If parallel straight lines are considered as belonging

to the same solid, and this solid has rectilinear movement, each of the lines moves along itself, or else they all describe surfaces which are called **parallel planes**. We have already considered the meaning of the word plane (137), so that we need not say more about it here.

401. Parallel planes agree in something which is not commonly called direction, because the same set of parallel planes may be described by each of a number of rectilinear movements having different directions. For want of a better word some writers say that parallel planes agree in **position.** According to this use of the word position, a plane which has a rectilinear movement in any direction always keeps the same position, however much its place is changed.

402. If two straight lines are not equal, the whole of one must be equal to a part of the other. The lines accordingly differ in something, which is called length. The **distance** of one point from another is the length of the straight line between those points. The distance of a point from any other geometrical object is its distance from the point of that object nearest to it. If a straight line is drawn from any point of a straight line or plane to the nearest point of another line or plane parallel to the first, it is **perpendicular** to both of the lines or planes it joins ; and if a perpendicular is drawn from each of any number of points in one of the parallel lines or parallel planes to the other of them, all these perpendiculars will be equal. The length of any one perpendicular is called the distance between the parallel lines or planes. The word perpendicular is sometimes used to mean vertical ; but a vertical line is perpendicular only to horizontal lines, and horizontal lines are perpendicular to vertical ones.

403. If a perpendicular is drawn between parallel lines, and the lines (or any solids to which we may suppose them to belong) rotate about this perpendicular as an axis (33), they will describe parallel planes, all of them perpendicular to the axis. Planes, then, may be described by a movement of rotation as well as by a rectilinear movement (400).

404. By the rotation of any thing about an axis, it is finally brought back to its first position. Hence we can divide every whole rotation into parts, which are called **angles**; but we cannot divide every whole rectilinear movement into parts called distances, because the movement may last so long that no statement of the whole distance it covers can be made. However, we may take any part of a rectilinear movement, and measure it off into distances on any one straight line described by means of it. The size of the moving body makes no difference in the distance it moves. In like manner, the size of a rotating body makes no difference in the angle through which it moves. If an object has turned half round about an axis, it has made half a rotation, whether it is a grain of sand, the Earth, or an object large enough to take in all the known universe.

405. Two different ways of dividing a rotation into angles are in common use in astronomy. The first is to divide a rotation into 360 equal angles, called **degrees**; each degree into 60 **minutes of arc**, and each of these minutes into 60 **seconds of arc**. The second way is to divide a rotation into 24 equal angles, called **hours**; each hour into 60 **minutes of time**, and each minute of time into 60 **seconds of time**. Hence, every hour, in this sense of the word, is an angle of 15 degrees; every minute of time is an angle of 15 minutes of arc, and every second of time is an angle of 15 seconds of arc.

406. For example, $\frac{1}{11}$ of a whole rotation is nearly 32 degrees, 43 minutes of arc, 38 seconds of arc, and $\frac{18}{100}$ of a second of arc; or, as it is usually written, $32^\circ\ 43'\ 38''.18$. It is also nearly 2 hours, 10 minutes of time, 54 seconds of time, and $\frac{55}{100}$ of a second of time; or, as it is usually written, $2^h\ 10^m\ 54^s.55$ Half a rotation is 180°, or $12^h$; $\frac{1}{4}$ of a rotation is 90°, or $6^h$; $\frac{3}{4}$ of a rotation is 270°, or $18^h$; $\frac{1}{10}$ of a rotation is 36°, or $2^h\ 24^m$; and so on. We must remember, when we use the names of divisions of time to denote angles, not to allow ourselves to be puzzled by their usual meanings. A fraction of a rotation is one thing, and

a fraction of the time occupied by the rotation is another. A wheel may go round ten times in what we usually call a second of time, and yet each of its rotations contains 24 hours, and therefore 86,400 seconds of time, understood in the sense of angles. Our measurements of time are made by means of the rotation of the Earth with respect to other objects, as was shown in the last chapter; but we shall see that when astronomers use the word hour as meaning $\frac{1}{24}$ of a rotation, this angle generally answers to the division of time called a sidereal hour, and not to an hour of mean time. If we were now to decide for the first time how a rotation should be divided, we should probably take some simpler method of doing it than any of those just described; but we must be content, for the present at all events, to follow the long established custom of mathematicians.

407. We sometimes reckon in decimal fractions of a degree, an hour, or a minute of arc or time, instead of reducing the fractions to a lower denomination. Thus $3^h.81$, or $3^h\ 48^m.60$, is the same as $3^h\ 48^m\ 36^s$. It may also be expressed by $57°.15$, or by $57°\ 9'$.

408. In rectilinear movement, all the points of the moving object go equally fast (395); but in rotation, some points do not move, and the others move slower the nearer they are to these (33). In rectilinear movement, all the straight lines of the moving object keep their directions unchanged, and all its planes keep their positions (401); while in rotation, no plane not perpendicular to the axis keeps its position, and no line, except the axis and the lines parallel to it, keeps its direction. We know nothing, of course, of any actual rotations, or rectilinear movements; these are only the names of movements which we find it convenient to consider as composing some of the actual movements about us (114).

409. Suppose one of the points of a rotating body to be moving at the same rate with each of the points of a body having rectilinear movement. When a whole rotation has been completed, this point will have described a line which, if it were straightened out, would be equal to the distance trav-

ersed during this rotation by the body having rectilinear movement. If the line is not straightened out, or rectified, according to the usual expression, it will form a ring round the axis. A ring of this kind is called the **circumference of a circle**. Very often, indeed, it is itself called a circle, for the sake of shortness; but a circle is properly that part of a plane inclosed by its circumference. We have seen that a circle is an ellipse without any eccentricity (145), or with both its foci at its centre. When a circle is described by means of a rotation, its **centre** is of course the point in the axis nearest to its circumference. For instance, if a horizontal circle is drawn by means of a pencil fastened to a thread tied to an upright pin, the pin will represent an axis of rotation, and the place where it pierces the paper is the centre of the circle. A diameter of a circle is any straight line passing through the centre and ending in the circumference on each side; and a radius is half a diameter.

410. The circumference of a circle may be considered in two ways; either as a line, having a certain length when regarded as rectified, or as a mere sign of the rotation by means of which it may be considered to have been described. In the first case, it may be measured in inches, or in any other measure of length; in the second case, it is divided, like a rotation, into equal parts called **arcs**, each arc answering to an angle and being called by the same name with that angle. Thus, an arc of 90°, or $6^h$, is a quarter of the whole circumference of any circle, no matter how large the circle may be.

411. When the circumference of a circle is regarded as a line of a certain length, its length may be compared with that of any one of its diameters, which are all equally long. It has been found that every circumference is a little more than three times as long as its diameter; but the length of the diameter is not contained in that of the circumference any number of times which can be stated in figures. For want of understanding that this is a known fact, many people have wasted their time in trying to square the circle, as it is called. The

ratio between the circumference and the diameter of any circle is commonly denoted by the Greek letter $\pi$, the name of which is Pi. The value of $\pi$ is very nearly $\frac{355}{113}$; that is, if any diameter is divided into 113 equal parts, there will be almost exactly 355 parts of the same length in the circumference. The figures in these numbers are easily remembered, from the order in which they come; 113, 355. The letter $\pi$ has other uses in astronomical computations besides that just explained; in particular, it often stands for certain angles of parallax (357).

412. If a circle rotates about one of its diameters as an axis, it describes a **sphere** (76, 159), the centre of which is the same with the centre of the circle. If a sphere is cut in two by a plane, the boundary between the two parts into which the surface of the sphere is thus divided must be the circumference of a circle. When one surface is cut by another, the boundary thus formed is called an **intersection**. The intersections of planes with the surfaces of spheres are generally called circles, although they are properly circumferences. When a plane passes through the centre of a sphere, its intersection with the sphere is a **great circle**. When a sphere is formed by the rotation of a circle, the diameter of that circle perpendicular (402) to the axis describes a great circle of the sphere. The ends of the diameter which serves as an axis are the **poles** of this great circle, and of all the small circles which lie in planes parallel to its plane.

413. Hence, if we draw a diameter through any sphere, its ends are the poles of the great circle and of all the small circles the planes of which are perpendicular to this diameter.

414. If two straight lines cross each other, and one of them is the axis of a rotation by which the other is carried round it, the moving line will describe a surface called the surface of a **double cone**. If a double cone is cut by a plane, the intersection of the two is a circle, an ellipse, a parabola, or a hyperbola (228), according to the position of the plane. All these figures are called **conic sections**. The parabola may be reduced to a straight line, the hyperbola

to two straight lines, and the circle or ellipse to a point, when the plane which forms the intersection cuts the cone into two or four parts exactly like each other.

415. If a rotating straight line is perpendicular to the axis of its rotation, it describes a plane to which the axis of its rotation is perpendicular (403), instead of a double cone. In this case, after a rotation of 90°, the rotating line is perpendicular to any line which at first coincided with it, and it is again perpendicular to it after a rotation of 270°.

416. What is called the **angle between two planes** is the amount of rotation about their intersection (412) as an axis which would bring one of them to coincidence with the other. If this angle is 90°, the planes are perpendicular to each other; and in this case the rotation may take place either way through 90° before the planes coincide. This may be illustrated by holding one leaf of a book vertical while the leaves on each side of it are horizontal (252, 255). But if the angle is not 90°, then the rotating plane will have less rotation to make one way than the other in order to come to coincidence with the stationary plane. In such cases the smaller angle of the two is usually considered as the angle between the planes.

417. The **angle between two straight lines** which cross each other is the amount of rotation which one of them would have to make, about an axis perpendicular to both of them, in order to come into coincidence with the other. This angle is the same with that between two planes, each of which contains one of the lines, and both of which are perpendicular to the plane which contains both of the lines. This may be illustrated by folding a piece of paper once, and setting it on a table so that the crease is vertical. The angle between the two lines drawn where the paper on each side of the crease rests upon the table (supposing these lines to be straight), is the same with that between the two parts of the paper; and the line of the crease is the axis about which the rotation which measures the angle is to be made. The crease, of course, must be made perpendicular to the lower edge of the paper.

418. A **plane polygon** is a part of a plane enclosed by straight lines; and a **spherical polygon** is a part of the surface of a sphere enclosed by arcs of great circles. These lines or arcs are the sides of the polygon; the angles of the spherical polygon are the angles between the planes of the great circles which form it, and those of the plane polygon are the angles between its sides (or between planes containing its sides and perpendicular to the plane of the polygon). In spherical polygons, the sides are not considered as distances, but as angles (410).

419. A **triangle** is a polygon with three sides and hence three angles. The angles of a plane triangle, taken together, always make just 180°; the angles of a spherical triangle, taken together, always make more than 180°. The sides and angles of a triangle are called its **parts**.

420. An angle of 90° is commonly called a **right angle**; and a **right triangle** is one which has a right angle for one of its angles.

421. Every polygon may be divided into triangles; and some of the parts of any triangle may be found by calculation if the others are known. Usually, it is enough to know three parts of a triangle to determine the other three.

422. Every line which is not straight may be regarded as having a particular direction at any one of its points. A straight line touching it at any point and having the same direction with it at that point, is **tangent** to it at that point. The point where the tangent touches the other line is called the **point of contact**. A line drawn through the point of contact and perpendicular to the tangent is **normal** to the other line.

423. In like manner, a plane may have a point of contact with some surface which is not a plane, but which is considered as having the same position (401) with the plane at the point of contact; the plane will then be tangent, and a line perpendicular to it will be normal, to the other surface at the point of contact.

424. Thus, if the top of a table is smooth and level, a per-

fectly smooth rounded stone lying on the table may be considered as having, at its lowest point, the same position as the upper surface of the table; and a vertical line through this point of contact between the stone and the table will be normal to the under surface of the stone as well as perpendicular to the upper surface of the table. If the stone is considered as divided by a vertical plane passing through its point of contact with the table, this normal line will likewise be normal to the intersection of the plane with the under surface of the stone, and perpendicular to the intersection of the plane with the upper surface of the table.

## CHAPTER IX.

### OPTICAL TERMS.

425. WHAT we call light is a movement of some kind, as yet little understood; but it has been found possible to lay down a number of rules about light which will hold good whatever may be learned about it hereafter.

426. Any line along which light travels is called a **ray** of light. What we commonly call a ray, or beam, of light, contains as many of these geometrical rays as we please. Rays of light continue straight as long as the matter through which the light is passing continues to be of the same kind. Any kind of matter through which light is passing may be called **a medium** of light; but two media are different even if the matter which composes one differs only in density from the matter of the other, and is like it in every other respect. A ray of light is said to be incident upon any surface on which the light shines.

427. Any object through which light cannot pass is called **opaque**. The light which comes to an opaque object may be absorbed by it (51) or reflected by it; generally it is partly absorbed and partly reflected. When most of it is absorbed, the object looks black; and the **colors** of opaque objects are due to the kinds of light which they reflect, some of them reflecting red light, some blue, and so on. Ordinary light may be separated into light of different colors in other ways than by absorption and reflection, as we shall see.

428. When any light is reflected, the angles of incidence and reflection are equal: that is, if a ray of light is normal (423) to the reflecting surface at the point where it strikes that surface, the light comes back as it went; or, in other words, the reflected ray coincides with the incident ray: and in any case, if we draw a line normal to the surface at the point

where the ray touches it, the reflected ray lies in the same plane with the incident ray and the normal line, and the incident and reflected rays make equal angles with the normal line. Hence, from all but very smooth surfaces, reflected light is thrown about in a variety of directions, so that any particular beam of light is broken up. Reflection of this kind is called **irregular**. But if a surface is very smooth, and a bright beam of light falls upon it from any particular direction, nearly all that part of the beam which is reflected at all may be reflected in some other particular direction. The reflecting surface, if seen from this last direction, will then seem to shine, but not to have any particular color. This sort of reflection is called **regular.**

429. Objects through which some light can pass are called **transparent.** The surface common (392) to two transparent media (426) is called a **refracting surface.** When light comes to a refracting surface, some of it is usually absorbed, some reflected, and some refracted. A ray of light is said to be **refracted** when its direction is changed by its passage through a refracting surface. The amount of the refraction of any ray of light at any refracting surface is the angle by which the direction it actually takes after passing that surface differs from the direction it previously had. This angle depends on the properties of the two media to which the refracting surface is common, and particularly on their density as compared with each other (426). Suppose that at the point where a ray of light passes through a refracting surface a line is drawn normal to that surface. If the ray coincides with the normal line before reaching the surface, this coincidence will continue beyond the surface, and the ray will not be refracted. If the incident ray is not coincident with the normal line, the direction of the refracted ray which has passed the surface will differ from that of the normal either more or less than before. If more, the medium from which the light comes is said to have more refractive power than that which the light enters; if less, the medium which the light enters has more refractive power than the other. For example, when a

slanting ray of light enters smooth and level water, the refracted ray is more nearly vertical than the incident ray; when a slanting ray of light comes from the water to the air, the refracted ray is less nearly vertical than the incident ray. Hence water is said to have more refractive power than air. As a general rule, if one object is denser than another, it has also more refractive power than that other object.

430. It may happen that a ray, on coming to a refracting surface beyond which lies a medium of less refractive power than the medium through which the light has been passing, is required by the laws of refraction to change its direction so much as not to pass through the surface at all. In this case, the surface becomes, for that particular ray, the surface of an opaque body, and the ray is reflected. This effect is called **total reflection**, and opticians often take advantage of it to make a glass prism serve instead of an opaque mirror.

431. A **prism**, properly speaking, is any geometrical solid described by a plane polygon having rectilinear motion. If the polygon is a triangle, the prism is triangular; and the glass prisms used for optical purposes are generally of this kind. If the triangle describing a triangular prism has one right angle, the prism is called a **rectangular** prism. A rectangular glass prism, if it is to be used as a mirror, is generally made so that the triangle by which it may be supposed to be described has the sides which form its right angle equal to each other. Now if a ray of light is supposed to enter the prism perpendicular to one of these sides, it will not be refracted (429), but will keep on in the same direction as before, to the side of the prism opposite to its right angle. It cannot pass through this side; for if it passed into the air at all, it would be more nearly perpendicular to the surface through which it had just passed than is consistent with the refractive power of glass as compared with that of air. Hence it is reflected; and as the reflecting surface is equally inclined to the other two faces of the prism, the ray leaves

the prism by its third side, to which the course of the light has now been made perpendicular; so that, as before, no refraction occurs. A good prism, used in this manner, reflects more light than the best opaque mirror.

432. When a glass prism is used, not to reflect light, but to refract it, the side of the prism through which the light enters is not set perpendicular to the direction from which the light comes, so that the light is refracted once on entering the prism; and the prism is usually made of such a shape that the light may be refracted again as it comes out of the prism into the air. Different kinds of light differ in refrangibility; that is, when several kinds of light come to a refracting surface, one kind is more refracted than another. An incandescent object often gives out light of a great many kinds mixed together; every solid or liquid object does this when it is made incandescent. One use of prisms is to separate different kinds of light from each other by means of their different refrangibilities. One of the kinds of light which come to a prism in some particular direction may be made (by total reflections within the prism, or otherwise) to keep on, after coming out of the prism, in this same direction; while each of the other kinds comes out in some other direction of its own, not very different, but still distinct, from that in which it entered the prism. But this depends on the shape of the prism, and on the direction in which the light comes to it. A flat piece of glass, with two plane faces parallel to each other, like a well-made window-pane, is one kind of prism. The light which passes through it is refracted at each face of the glass; but the second refraction restores each kind of light to the direction it had before the first refraction, so that the different kinds of light are not turned into different directions by their passage through the glass. In fact, as every one knows, an ordinary window-pane has no very noticeable effect of any kind on the appearance of objects seen through it; and we need not stop to consider the small effects which it may be shown to produce.

433. A beam of light is said to be **dispersed** when the

directions of the various kinds of light composing it are unequally changed. When dispersion is occasioned by refraction, its amount is partly dependent on the nature of the refracting medium. For example, one kind of glass, called crown glass, has less dispersive power than another kind called flint glass. Hence, if different kinds of light come all in the same direction to a surface of flint glass, and pass through it, their directions in the glass will be more unlike each other than they would have been if the glass had been crown glass. By taking advantage of this fact, we can put pieces of different kinds of glass together so that they will refract one of the kinds of light coming to them in any particular direction about as much as they refract another; or so that one kind of the light which comes to them in some particular direction will leave them in about the same direction, while they change, more or less, the directions of the other kinds of this light; or so that the light may be both refracted, as in the first case, and dispersed, as in the second.

434. It appears from the account just given of reflection and refraction, that any very smooth reflecting or refracting surface may be sending out a great deal of light in some particular directions, but in no others, so that it looks bright from one place and not from another. But a surface not very smooth, that of ordinary wood, metal, or cloth, for instance, may be considered as sending out in all directions some of the light which comes to it; and the surface of a body which gives out light of its own also sends out this light in all directions. When light is sent out in all directions from any particular point, some of it may be stopped at once by the very body to which this point belongs; and other rays of it may be absorbed, reflected, or refracted by the bodies they meet after having travelled to a greater or less distance. That part of the light sent out from any particular point, and coming straight to any particular surface which we may be considering, is called a **divergent pencil of rays** incident upon the surface from the point. Every pencil of this kind,

then, is considered as beginning at some point and gradually spreading out until, when it reaches some surface, it is large enough to cover it exactly. Other pencils of rays may of course be incident at the same time on the same surface. All these pencils coincide at this surface, and separate from each other more and more as we follow their courses backward to the points from which they start.

435. Now suppose the surface on which a divergent pencil is incident to be the pupil of a man's eye, and the point from which the pencil starts to be on the surface of a hill ten miles away. It is clear that if straight lines are drawn from this point to opposite sides of the pupil which receives the light, these lines will be nearly parallel; for in the course of ten miles they have separated from each other only about one-tenth of an inch. So, too, if a divergent pencil of light starts from a point in the Moon and is incident on the roof of a large building, the rays of this pencil which diverge most from each other are still very nearly parallel. The largest astronomical instruments are only a few feet across: so that it is obvious that all pencils of light coming to these instruments from points in the celestial objects which are observed through them may be considered as made up of rays of light parallel to each other. A pencil, the rays of which are considered to be parallel to each other, is called a **parallel pencil**.

436 By means of properly shaped reflecting or refracting surfaces the directions of the rays of any pencil may be changed with respect to each other. The instruments made with reflecting surfaces, suited to this purpose, are called **mirrors** or **specula**; those with refracting surfaces are usually of the kind called **lenses**. The surface of a mirror may be either plane, convex, or concave. A rounded surface is **convex** on the side on which a plane must lie in order to have a point of contact with it (423), and **concave** on the other (185). The surface of a globe is one kind of convex surface, and that of the air which touches it is one kind of concave surface. A lens may have both its opposite surfaces

convex, both concave, one convex and the other concave, or one plane and the other convex or concave. If both were plane, it would be a prism rather than a lens. If one is convex and the other concave, the lens may be considered on the whole convex if the convex surface is the more rounded of the two, and concave, if the concave surface is the more rounded.

437. A concave mirror, or a convex lens, makes the rays of any pencil of light incident upon it less divergent than they were before. It may make them parallel, or even convergent, so that they come together more or less exactly at some point in their new course. Beyond this point the pencil is again divergent; but it usually forms the whole of the light diverging from that point, while it was only part of the light diverging from the point where it began (434).

438. A convex mirror, or a concave lens, makes the rays of any pencil of light incident upon it more divergent than they were before. It may turn a convergent pencil into a parallel or into a divergent pencil.

439. By putting together two lenses made of different sorts of glass, we can obtain a lens which will act in either of the ways just described without noticeably dispersing the different kinds of light which we may regard as reaching the lens in the direction of any particular ray (433). A lens of this kind is called an **achromatic** lens.

440. The chief difficulty in explaining the facts of optics is that pencils and rays of light are apt to be mistaken for each other. To avoid this difficulty as much as possible, we will hereafter take little notice of rays, and consider only the course of pencils of light. To show how an image of an object may be formed by means of the pencils of light coming from different parts of that object, we have only to shut out from some room or small building all light whatever, except what comes through a small hole left in one side of the room, and facing towards some object — a tree, for example — which is seen against bright sky or clouds. An image of the tree will be thrown upon any thing in the room which may be

opposite the hole; a white screen of some kind will answer best to receive the image. In this case the light by which we see the image comes from behind the tree, and the image itself is a kind of shadow. Still, as the tree really reflects some light towards the hole, although still more light comes from behind the tree, we may speak of pencils of light coming from the tree to the hole. The pencil which starts from the tip of one of the tree's branches, and passes through the hole, makes a little spot of dim light upon the screen. This little spot forms the image of the tip of the branch, and looks dark upon the screen because there is brighter light around it coming from behind the tree. The image of every point on the surface of the branch turned towards the hole is likewise a little spot of dim light on the screen. These spots overlap each other, more or less, according to the size of the hole; so that if the hole is too large, no image can be seen. But if the hole is small enough, the image of any particular point in the branch will not cover up the images of any other points except those close to it. Accordingly, the shape of the branch will be traced out, though not very clearly, upon the screen. During eclipses of the Sun, the openings among the leaves of trees may occasion the appearance of little sickle-shaped images upon the ground beneath them. This effect depends on the principles just stated.

441. The images upon the screen will be **inverted**; that is, the pencils coming from any two points outside of the hole must cross each other at the hole, so that if one of the points is above the other, its image must be below that of the other; and if one is east of the other, its image must be west of that of the other. Hence the picture on the screen is upside down, and its sides stand the contrary way from those of the object which the image represents.

442. If we wish to make the image plainer and yet keep it from being confused, we must make the hole larger, so that more light may come in, and fill it up with a convex (436) lens; a lens which is also achromatic (439) will, of course, be best. This lens must have enough refractive power to

make the rays of each pencil come together in a single point somewhere within the room. If the pencils all start from points about equally far from the lens, the points where the rays of each of them all meet again will be about equally far from the lens; for instance, if any pencil starts from a point two hundred feet from the lens, and its rays all meet again inside the room and ten feet from the lens, the rays of any pencil incident upon the lens from another point about two hundred feet away from it will also meet again inside the room and about ten feet from the lens. The lens, if it is a good one, will not greatly alter the general course of each pencil; it will only alter the shape of the pencil, making it convergent, instead of divergent, as before (437).

443. If the screen is held close to the lens, the image will be confused, because each pencil will make a large spot on the screen, and these spots will overlap each other; but if the screen is then gradually moved away from the lens, the spots will grow smaller and smaller, while the image grows more and more distinct. When the screen is held so far from the lens that each spot may be extremely small, the image will be much more distinct than it would be without the lens, even if the hole were so small that only just enough light could come in to make the image appear at all. If the screen is moved still farther away from the lens, the pencils will again widen out and the image will become confused.

444. A dark box, into which light is admitted through a convex lens, so that images may be formed on a screen inside, is called a **camera obscura**, or very often simply a **camera**. Instruments of this kind are used in making photographic pictures. But for various reasons, it is difficult to make a camera which will represent an extensive view correctly. The shapes of objects, especially of those towards the border of the picture, are apt to be altered even in the best cameras. To correct as far as may be this change of shape, which is called distortion, several lenses are generally used instead of one.

445. Any point where the rays of a pencil of light are

made to meet by means of a lens or mirror is called a **focus.** The name of focus is also given to any point from which a pencil starts, or is made to seem to start. A concave lens, for instance, which makes a pencil more divergent than it was before (438), makes the pencil seem to start from a point nearer to the lens than that from which it really starts ; and this apparent starting-point of the pencil is often called a focus.

446. What is usually meant by the **focal length** of a lens or of a mirror, is the distance from it at which would be found the focus given by the lens or mirror to a parallel pencil of light incident upon it (435).

447. The eye of an animal consists in part of an apparatus like a camera obscura. The screen on which the images of objects are formed within the eye is called the **retina.** Images formed on the retina are of course inverted (441). The question is sometimes asked why we do not see objects upside down, as their images are placed on the retina. But this question is rather absurd, for no eye sees its own retina, or can tell any thing about the shape and place of an image formed upon it. We see objects outside of us by means of their images ; we do not see the images themselves. How it is that we see any thing at all has not yet been fully found out.

448. There is a spot in the retina on which an image may be formed without making the eye see the object by which that image is formed. Since we commonly use both eyes in looking at any object, we see it with one eye or the other, however we stand with respect to it. But if one eye only is used, an object which is in sight when it is either directly in front of the eye, or far towards its outer side, may be out of sight when it has a certain direction from the eye, between the two directions just mentioned. For instance, when a ship is sailing past an observer at a considerable distance, if he closes one eye and keeps the other eye still, the ship will pass out of his sight, and come into sight again when its image has crossed the spot on the retina where it may be formed without making the ship visible.

449. The distance which we suppose ourselves to see between any two points is merely an angle. Suppose a straight line to be drawn from each point to its image on the retina. If these two lines do not cross, they must at all events pass close by each other somewhere in the eye. Now the angle between the direction of one line and that of the other, or, in other words, the angle between one line and a line drawn across it parallel to the other (417), is all that we can know, by the mere sense of sight, about the distance between the two points from which the lines are drawn.

450. If these points are near enough to the observer to make a noticeable difference between their directions from one of his eyes and from the other, he can then make an estimate of their actual distance from him even without moving his head; and if he moves a little, he sees them in so many different directions that it is easy for him to judge pretty correctly how far away they are. When he knows this, he can tell how far apart they are by means of the angle between the lines drawn from them to either of his eyes. All these calculations are made without the need of any distinct thought at all; in a rough way, it is true, but still correctly enough for the ordinary wants of life. Calculations of a like kind, made accurately from the angles found by exact observation with instruments, give us the means of finding the distance from us, and the distance apart, of objects far from the places where the observations are taken.

451. Most people are in the habit of thinking that they see actual distances; but the fact is that their knowledge of these distances, so far as it is got by means of sight, depends on observations of parallax (357), and on rough calculations made from these observations, so quickly and easily that neither the observations nor the calculations are noticed, and the distances measured by means of them are thought to have been seen. Before people can learn to draw, they have to break themselves of the habit of overlooking what they really see (267).

452. The angle between the straight lines drawn from any

two points to a third is called either the **visual angle** or the **angular distance** between the first two points seen from the third. An angle is properly no distance at all. Distances are amounts of rectilinear motion, and angles are amounts of rotation, or, as it is also called, angular motion. However, the phrase angular distance may sometimes be a convenient one to use.

453. When the thickness of a pencil of light is small compared with its length, we may speak of the direction of the pencil without any great want of exactness, even if it is not a parallel pencil; for none of the straight lines drawn from one end of it to the other can differ much in direction. Accordingly, we may say that the angular distance between two points seen by any observer is the angle between the pencils of light which reach his eye from those points.

454. The **angular diameter**, or, as it is often called, the **apparent diameter**, of a celestial object, is the angular distance between the ends of any one of its diameters which is drawn perpendicular to the direction of the object from the observer. That is, this apparent diameter is the angular distance between any two opposite points on the limb of the disk of the object observed.

455. In order to see any object distinctly, the eye must bring each pencil of light which comes to it from that object nearly to a focus (445) upon some part of the retina. If a pencil of light is strongly divergent when it enters the eye, it reaches the retina before it has been brought to a focus. Hence an object held less than about three inches from an ordinary eye cannot be seen distinctly. Ordinary eyes can adapt themselves to pencils which are either parallel or only slightly divergent. Near-sighted eyes can adapt themselves only to divergent pencils, and sometimes have to be assisted by concave lenses, so that the pencils which reach them may be made more divergent than they would be except for the lenses.

456. If a convergent pencil of light enters an ordinary eye, it is brought to a focus, beyond which it becomes a divergent

pencil, before reaching the retina. Hence, if an object is looked at through a convex lens of such power that it turns the divergent pencils reaching it from the object into convergent pencils, the object ordinarily looks indistinct. But far-sighted eyes can adapt themselves to slightly convergent pencils of light, and not to divergent pencils; so that they have sometimes to be assisted by convex lenses. They can usually see distant objects without assistance, because a pencil of light reaching the eye from a point far away may be considered as a parallel pencil.

457. If a point is sending out light in all directions, then, at any particular distance from this point, its light must be spread out over the surface of a sphere enclosing the point at that distance. Now, as is shown in works on geometry, the surfaces of spheres are to each other as the squares of their diameters, or as the squares of their radii. That is, if the diameter of one sphere is twice that of another, it will have four times as much surface; if the diameter of the first sphere is five times as long, its surface will be twenty-five times as great, as that of the second sphere. Hence the brightness of a single point will generally lessen in proportion to the increase of the square of its distance from the eye. But the visual angle between any two points of an object looked at will also diminish at the same rate. Hence an object does not necessarily look fainter at a distance than close at hand; for the closer packing of its points in the image of it formed on the retina will make up for the greater dimness of each point when seen from a distance. But much of the light of a distant object may be absorbed on its way to the eye, and this is the reason why distant terrestrial objects look fainter than others of really equal brightness which are close at hand.

458. Celestial objects, however, do not become dimmer in proportion to their distance. From any place just outside the Earth's atmosphere, the Moon would probably look as bright, though not as large, as it would from a place within ten thousand miles of it; for although it is possible that some

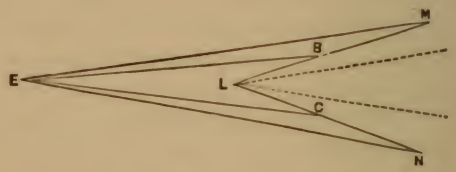
light is absorbed in passing through the ether, or whatever may fill the spaces between the various celestial objects, this absorption is evidently small. If it were large, the Moon would look decidedly brighter in perigee than in apogee (177, 191).

459. The stereoscopic effects, as they are called, which depend on our ordinary use of two eyes at the same time, have so little to do with astronomical observations that they need not be described here.

## CHAPTER X.

### THE TELESCOPE.

460. MOST people have occasionally looked through convex lenses, and are aware that such lenses usually magnify the objects seen through them. That is, a convex lens usually increases the angular distance between any two points in an object looked at through the lens. The reason for this is as follows: —




If we suppose the eye to be placed at E, in the figure above, the visual angle (452) between two points, one at B and the other at C, will be the angle BEC, formed at E by the lines BE and CE. Now suppose a convex lens to be placed between the eye and the object to which the points B and C belong. The effect of this lens will be to make the pencil of light reaching it from B less divergent than it was before passing the lens. The same effect would have been produced without the lens if the point B had been moved farther away, to some such point as M in the figure. So, too, the effect of the lens upon the pencil reaching it from C might be produced without the lens if C were removed to some such point as N in the figure. The proper places for these points M and N may be determined by calculations for which there is no room in this work. They depend on the exact shape of the lens, the material on which it is made, and its place with respect to the points B and C. But M, N, B, and C, will all

lie nearly if not exactly in one plane; and we will suppose them to lie exactly in one plane. Then, if we draw lines from M through B and from N through C, these lines must cross each other at some such point as L in the figure. This point L will be in fact somewhere near the middle of the lens; and it is called the optical centre of the lens.

461. Now if the eye were at L, the visual angle between B and C would be BLC; and this visual angle would remain unchanged by the removal of the points B and C to M and N. But as the eye is at E, there may be a difference between the visual angle BEC of the points B and C and the visual angle MEN of the points M and N. In ordinary cases, such as that represented in the figure, the angle MEN is larger than the angle BEC. Hence the lens magnifies the distance between the points B and C, and in like manner magnifies the distance between any two points in the object looked at through the lens; so that the object looks larger than it did before the lens was placed between it and the eye. A convex lens used in this way does not invert the objects seen through it. In the figure, for example, M is above N just as B is above C.

462. Now suppose that the lens is taken away and that the eye is brought from E to L. The visual angle between the points B and C is now BLC; and this angle is not only larger than BEC, but larger even than MEN. This appears by the dotted lines drawn from L parallel to ME and NE so as to make an angle at L equal to the angle MEN. It seems, then, that an object seen through a convex lens looks no larger than it would look if the lens were taken away and the eye brought a little nearer to the object. We notice the magnifying effect of a lens because we are not used to having lenses constantly placed between us and other objects and taken away again; but we are so used to moving a little one way or the other that we do not notice how much larger an object looks when it is a few inches from our eyes than when it is a yard or two away (267).

463. A convex lens, however, becomes of real service as a

magnifier when the eye has already been brought as near the object to be observed as it can be brought without making the object indistinct (455). Writers on optics sometimes speak as if the eye were always brought as close as possible to the object observed. They say, accordingly, that a convex lens magnifies only because it enables the eye to be placed closer to the object than it could otherwise be placed. But this is a careless statement; and every one who has amused himself with a magnifying-glass knows that without changing the distance of his eye from the letters of a book he can magnify them by means of the lens.

464. A concave mirror magnifies objects held near it for much the same reasons as those which account for the like effect of a convex lens. But this use of concave mirrors is not required in the construction of astronomical instruments.

465. For astronomical purposes, we need instruments which will magnify distant objects. Now every pencil of light which reaches our instruments from a distant object is practically a parallel pencil (435). If, then, we view a distant object through a convex lens held near our eyes, we shall merely make our view of the object indistinct; for each parallel pencil of light from the object will become a convergent pencil after passing the lens (437, 456). But suppose that the focal length of the lens (446) is less than its distance from the eye. Every pencil of light which then reaches the eye from any distant object seen through the lens will be a divergent pencil starting from the focus to which the lens brought it before it reached the eye.

466. Suppose that the pencil of light from the point B is made by a lens to converge to the point M, while the pencil incident on the same lens from the point C converges to N. If we draw the lines MB, NC, their point of intersection, or at

all events the place where they come nearest to each other, will not be far from the middle of the lens. We will call this point L, as before. After passing the focus M, the light from the point B will form a divergent pencil starting from M, not in all directions, but only along the continuation of those lines by which it came from the lens to M (437). If any part of this divergent pencil enters an eye placed at E, it will appear to have come, not from B, but from M. In like manner, any light reaching the eye through the lens from the point C will seem to have come from N. It must be remembered that the lines in the figure do not represent rays of light, but are merely drawn to show the comparative size of certain angles. The direction of almost every ray must be changed by its passage through a lens.

467. The lines BM and CN cross each other at L, so that the image at M of the upper point B is below that at N of the lower point C. It appears, then, that objects will be seen inverted (441) when looked at through a lens which makes pencils of light from them convergent, and is held so far from the eye that before reaching it these pencils have passed their foci and have again become divergent. The difference between this use of a lens and its use in a camera obscura is that when an image is formed on a screen, it is shown by irregular reflection (428) from the screen, so that it may be seen by an eye placed anywhere within view of it; while if it is formed in the air it can only be seen when the eye is placed on that side of it towards which the pencils of light from it proceed.

468. The angle MLN is evidently equal to the angle BLC; the proof of this equality may be found in geometrical text-books, if it is wanted. Hence the angle MLN may be considered as the visual angle between the points B and C, viewed from the point L; and if these points B and C are supposed to be distant (465), it will make little difference in the size of the visual angle between them whether we suppose them to be viewed from L or from E, since the distance between the eye and the lens will be small compared with the

distance of either of them from the object looked at. Accordingly, we may say that MLN is equal to the visual angle between B and C, viewed without any lens. MEN is the visual angle between M and N ; and hence is the visual angle between B and C viewed through the lens. Now if M and N are just half-way from L to E, the angles MLN and MEN will obviously be equal ; the proof of this equality is given in works on geometry. In the case just supposed, the lens will neither magnify nor diminish a distant object viewed through it. If M and N are less than half-way from L to E, the lens will diminish ; if more, it will magnify. It seems, then, that the eye must be placed close to the image of an object formed behind a convex lens, in order that the lens may make the object look larger. But if this is done, the view becomes indistinct (455). This difficulty, however, can be got rid of by means of another lens, used in the manner already described (460), but in this case to magnify the image of an object instead of the object itself.

469. An ordinary **astronomical refracting telescope** accordingly consists of two lenses, or rather of two combinations of lenses, so that the various defects which the instrument would otherwise have may be corrected as far as possible. One of these combinations of lenses is called the **object-glass**, and is used to form the image, which is then magnified by the other combination of lenses, called the eye-piece. The object-glass is usually made achromatic (439), and the lenses of which it is composed are larger than those of the eye-piece. The width of the object-glass is called the **aperture** of the telescope, and its focal length (446) is often called the **focal length** of the telescope. Every telescope is usually provided with several eye-pieces of different magnifying powers.

470. In the following figure, the telescope is supposed to reach from O to L ; O being a point somewhere near the middle of the object-glass, and L a point somewhere near the middle of the eye-piece. The visual angle between B and C as seen from E is of course BEC ; that between B and C

as seen from O is BOC. In the figure, BOC is decidedly larger than BEC, as is shown by the dotted lines within BOC,

which are parallel to the dotted lines BE and CE, and therefore make an angle with each other equal to the angle BEC. But the points looked at with a telescope are always much farther from it in proportion to its length than are the points B and C from O in proportion to the distance OL. In practice, then, the angle answering to BOC is about the same as the visual angle between the points answering to B and C, looked at without a telescope.

471. Let us suppose that the image of the point B is formed by the object-glass at M, and that of the point C at N. The angle MON is equal to BOC (468), and therefore equal to the visual angle between B and C seen without the telescope. Now if the eye were at L, the visual angle between M and N would be MLN; and if the eye-piece is placed at such a distance from M and N as to be most serviceable in magnifying the visual angle between them, the effect will be the same as if the eye were actually at L. The visual angle between B and C as seen through the telescope will accordingly be found by drawing from E a line EP parallel to LM, and another line EQ parallel to LN. The angle PEQ is then equal to MLN, and therefore to the visual angle between B and C as seen through the telescope, B appearing to lie somewhere along the line EP, and C somewhere along the line EQ.

472. An eye-piece, or any convex lens used in magnifying, is most effective when it is placed at a distance from the object observed equal to its own focal length (446). If the focal length of the eye-piece is the same as that of the object-glass, the points answering to M and N come half-way between the object-glass and eye-piece. In this case, the angles MON and MLN would be equal (468), and the tele-

scope would neither magnify nor diminish. If the shapes of the object-glass and eye-piece are such that the focal length of the eye-piece is one quarter of that of the object-glass, the points M and N (provided that they are as near each other as is always the case in a telescope) will be almost exactly four times as far from O as from L; the angle MLN will then be very nearly four times as great as the angle MON, and the telescope will be said to magnify four times. That is, the visual angle between any two points of a distant object will be made about four times as large as before by looking at the object through the telescope held in the usual way. If the object-glass is turned towards the eye, and the eye-piece towards the object, the telescope will diminish the apparent width of the object to a quarter of what it seemed to be before.

473. The general rule with respect to the **magnifying power** of any telescope is, that the telescope magnifies as many times as the focal length of the eye-piece is contained in that of the object-glass. Hence no telescope can be said to have any particular magnifying power; for all we have to do in order to change that power is to unscrew the eye-piece and put in another. If the focal length of the new eye-piece is less than that of the old one, the magnifying power of the telescope is increased by the change; if greater, it is diminished.

474. It appears by what has been said that the aperture of a telescope (469) has nothing directly to do with its magnifying power; for the focal length of a lens depends on its shape, and not on its size. Any particular eye-piece will magnify twice as much, when applied to a telescope the object-glass of which is so constructed as to have a focal length of twenty feet, as it will magnify when applied to a telescope the focal length of which is only ten feet; although the object-glass of the first telescope may be two inches, and the object-glass of the second two feet across. But if an object-glass is very large, it is found best in practice to give it such a shape that its focal length will be considerable. An

object-glass two feet across would in fact have a focal length of about thirty feet. In former times (before achromatic lenses were made), object-glasses which would now be considered small ones were made of great focal length when a high magnifying power was wanted ; but this made them inconvenient to use. Modern opticians are not forced to get magnifying power by making object-glasses of great focal length. Instead of this, they make eye-pieces of small focal length.

475. The use of large object-glasses is not to magnify greatly, but to admit a great deal of light. If the images formed by the object-glass of a telescope are not bright, they will look very dim when they are magnified by a powerful eye-piece. In this way a large object-glass may be said to increase the magnifying power of a telescope, since it allows us to use strong eye-pieces. However, the chief advantage of a large object-glass is that it helps us to see faint objects which could not be seen at all with a small object-glass. In examining such objects, eye-pieces which magnify little are preferred. Hence it often happens that the eye-piece actually used with a very large telescope is less powerful than one which may be used with a small telescope when bright objects are looked at ; the Moon, for example, or a large planet.

476. The Earth's atmosphere is one great hindrance to the use of high magnifying powers. All the disturbances in it keep the transparency and the refracting power of its different parts in a continual state of change ; and the solid and liquid particles which float in it add to the effect of these disturbances. This effect increases with the increase of the magnifying power applied by means of a telescope to any celestial object. Hence it is seldom possible to use eye-pieces magnifying more than five hundred times, even with the best and largest telescopes. Now in order to see the Moon as it would appear, without a telescope, at a distance of forty miles (190). we must apply to it a magnifying power of six thousand ; in other words, a power twelve times as great as any which the ordinary state of the air will allow us to use with advantage.

477. For the purposes of sight-seeing, a small telescope, with eye-pieces magnifying from fifty to two hundred times, is nearly as satisfactory as the largest telescopes that can be made. The use of great instruments is not to display wonderful sights in the sky, but to enable astronomers to see little things which are of importance in helping on the study of the construction of the universe. These little things are apt to be entirely overlooked by persons who have not learned to use telescopes for astronomical purposes, and even when they are seen are not thought interesting (388). In short, large telescopes are meant for work and not for show.

478. A **reflecting telescope** differs from a refractor in forming images by means of a concave mirror instead of an object-glass. The light which this mirror reflects may be again reflected by other mirrors, so that the place of the image may be either behind the chief mirror (in which there must then be an opening for the passage of the light after its second reflection), or at one side of the tube of the telescope. If no secondary mirror is used, the chief mirror may be set a little slanting in the tube, so that the image is formed near one side of the mouth of the telescope. Whatever arrangement is adopted, the image is viewed, as in the refracting telescope, through an eye-piece placed near it, which may be of any power thought to be advantageous.

479. A reflecting telescope must be much larger than a refractor which gives equally bright and distinct images; for more light is lost in the process of reflection than in that of refraction. The largest reflecting telescope hitherto built has a mirror six feet across; while the aperture of the largest refractors is little more than a third as much.

480. Spy-glasses and opera-glasses are seldom used as astronomical instruments, so that little need here be said of them. The spy-glass is an astronomical telescope with additional lenses so placed that a second image is formed by the light proceeding from the first image. This second image is not inverted, so that when it is viewed through the eye-piece the object towards which the telescope is pointed is seen

upright and not upside down. Some light is lost by this arrangement, but as spy-glasses are meant to be used in magnifying objects seen by day under a strong light, this loss of light is unimportant. In astronomical work, on the other hand, all the light that can be had is usually wanted, and the inversion of the object looked at is of no consequence.

481. If the eye-piece of an astronomical telescope is set farther back from the image than usual, each pencil of light which comes out of it is convergent, so that nothing distinct can be seen by looking into the eye-piece in the usual way. But if a screen is held at a certain distance from the eye-piece, a second image will appear upon the screen (50). If the screen is not used, this second image might be magnified by a second eye-piece placed beyond it; and this arrangement of lenses is like that of an ordinary spy-glass.

482. In the opera-glass, the eye-piece is a concave lens placed at a distance from the object-glass less than the focal length of that glass. No image is formed, therefore, because each convergent pencil of light from the object-glass is turned into a parallel pencil by the eye-piece, before reaching the point where it would otherwise have come to a focus. But the direction of this parallel pencil is not usually the same as the direction which it had before reaching the object-glass and becoming convergent. Hence the angle between the direction of this pencil, and the direction of some other, may be increased by their passage through the lenses of the instrument; and in this case the visual angle between the points from which the pencils come is increased by these lenses, and the instrument magnifies. A telescope made in this way is short and easily handled; and it does not invert the objects seen through it. It is therefore convenient for many purposes, especially when mounted as it usually is, in the same frame with another like it, so that both eyes may be used at once. It has defects, however, which make it inferior for astronomical use to the ordinary refractor. For example, when we wish to make measurements of any kind by means of a telescope, we must put sights of some sort into the instrument.

This could not be done with an opera-glass, but may be done with an ordinary telescope, in the manner described below.

483. If a mark of any kind, such as a metal ring, a fine wire, a spider's thread, or a line marked on a glass plate, is put into the tube of a telescope at the place where images of distant objects are formed by the object-glass, these images and the mark will be equally magnified by the eye-piece. By moving the telescope so that some point in the mark coincides with some point in an image, and afterwards bringing the same point in the mark, by a second movement of the telescope, to coincidence with another point in the same image or a different one, we can measure the visual angle between the two points to which the mark has been brought. For the angle through which the telescope was carried by its second movement can be measured in any one of a number of ways; and the visual angle between the points is either the same as that through which the telescope was moved, or can be found from it by calculation.

484. Suppose, for instance, that we wish to know the angular diameter (454) of the Moon. If we put a spider's thread across that part of the tube of a telescope where the image of any distant object will be formed, this thread will appear, when the telescope is pointed towards the Moon, as a black line crossing its disk. Now let the telescope be moved so that the thread is a little beyond the Moon's preceding limb (183). If we now leave the telescope untouched, the Earth's rotation will move it, so that the thread will be carried across the Moon's disk from side to side. We can tell by calculation from the known movements of the Earth and Moon how much any terrestrial place moves with respect to the Moon in a given time. Hence if we note the time occupied by the thread in crossing the Moon's disk, we can calculate the apparent diameter of that disk as seen from the place of observation.

485. All astronomical measurements are made by methods resembling this in principle; we shall have occasion here-

after to notice a few of these methods, but most of them are of no interest except to practical astronomers.

486. The **line of sight** through a telescope may be variously defined; but in practice it is the straight line drawn from any point in a distant object to the image of that point formed by the object-glass, when that image is formed at some point chosen for the purpose, and marked by the sights put into that part of the tube of the telescope where the object-glass forms images. If the object-glass and these sights move with respect to each other in the telescope, the line of sight is altered by the movement. Movements of this kind may be occasioned by changes of temperature, which expand or contract unequally the different parts of the telescope, by the weight of the instrument itself, which will bend it differently according to the different ways in which it may be pointed with respect to its support, or by the accidental jarring of this support, or of any part of the telescope. But if a telescope is well made, its line of sight will keep its direction long enough at a time to allow correct measurements to be made by means of the marks used for that purpose, as already explained.

487. All that can be seen through a telescope at once is said to be in the **field** of the telescope. The field is large or small, according to the size of the greatest angles between objects in the field. The field is generally only a few minutes of arc in width when an eye-piece of high magnifying power is used.

## CHAPTER XI.

### THE SPECTROSCOPE.

488. IN the ordinary use of a telescope, it is desirable that the light should pass through it with as little dispersion as possible. But when we wish to study the chemical properties of distant objects, and not merely their shape and size, we must begin by finding out what different kinds of light we receive from them. This can be done by making use of a prism, as we have seen (432).

489. A prism made for the purpose of scientific research is usually a piece of glass having two plane refracting surfaces which are not parallel with each other. The prism is so placed that the light which is to be examined may fall on one of these surfaces and be refracted into such a direction as to pass out of the prism by the second surface. By this process, the general direction of the light is usually made different from that direction in which it came to the prism; but if it is desirable to avoid this change of direction, it may be avoided by means of total reflections or by the combination of prisms made of different kinds of glass (431, 433). Whatever the general direction may be in which a beam of light leaves a prism, the different kinds of light in that beam will have been turned into slightly different directions by the refractions which the beam has undergone. That is, the beam will have been dispersed. Suppose it to have come through a round hole in the wall or in a metal plate placed before the prism. It will then be a round beam, and would make a round spot of light on a screen held perpendicular to it, if it had not been dispersed. But after passing through the prism it will no longer make a single round spot of light upon the screen, unless it happens to contain only one kind of light. In that case, the prism cannot disperse the light.

Suppose, however, that there are two kinds of light in the beam. Then, after passing the prism, the beam will be separated into two beams having slightly different directions, and therefore getting farther and farther apart as they go on beyond the prism. Each of these beams will be round, and as large as the whole beam was before it was dispersed ; but it will not be as bright as the whole beam, because it contains only part of the light which reached the prism. Now if a screen is held close to the prism, it will cut off these two beams before they have fairly separated from each other, and the spot of light formed by one beam will partly overlap the spot formed by the other. If we move the screen away from the prism to a distance at which the two beams are wholly separated from each other, there will be two round spots of light on the screen.

490. The directions of both the refracted beams will be perpendicular to the direction of the line which forms the intersection of the two refracting planes through which the light has passed, provided that the direction of the beam incident on the prism was perpendicular to this line. If the prism is made so that its two surfaces used in refraction come together and form an edge, then, supposing the edge to be horizontal and its direction to be perpendicular to that of the incident beam, one of the two spots on the screen will be over the other ; if the edge is vertical and the incident beam is horizontal, the two spots will be on a level.

491. If the two kinds of light differ very little from each other in refrangibility, the directions of the two refracted beams will be so nearly the same that they will not be separated from each other even at a great distance from the prism. In this case, we must bring the light to the prism through a narrow slit instead of through a round hole ; placing the slit with its long edges parallel to that edge of the prism where its two refracting surfaces meet. The incident beam will then be flat and thin ; the two refracted beams will also be flat and thin, and will soon be clear of each other ; while if the slit had its long edges perpendicular to the intersection

of the refracting surfaces of the prism, it is plain that the thinness of the beam would be of no service (490).

492. The light which has been dispersed by passing through a prism may be looked at with a telescope placed in its path, instead of being received upon a screen. The appearance it presents is called a **spectrum**, whatever method of examining it may be employed. The different kinds of light differ in color as well as in refrangibility. Blue light, for instance, is more refrangible than yellow, and yellow than red light. If a spectrum is formed by a beam which contains only three kinds of light, one blue, one yellow, and one red, the spectrum will consist of a blue spot, a yellow spot, and a red spot. The shape of these spots will usually depend on the shape of the opening through which the light comes to the prism ; if this opening is a slit, the spots will be narrow strips of light. But if the opening is large enough to allow us to see through it the whole of the surface from which the light comes, we shall then have a spectrum made up of three separate images of that surface ; one blue, another yellow, and the third red.

493. Suppose, however, that instead of three kinds of light very different from each other in refrangibility and in color, the beam incident on the prism contains three kinds of light almost exactly alike in these respects ; three kinds of yellow light, for instance, all nearly of the same shade of yellow. In this case, if the light comes through a slit, the spectrum will consist of three narrow strips of yellow light, side by side, and close to each other. But if we let in the light through a larger opening, we shall not have, as before, three separate images of the object from which the light is sent out ; for the images will be so close together as to overlap, and will make a confused spot of yellow light.

494. The spectra of incandescent solids and liquids consist of a great variety of kinds of light, each of which differs so little from those most like it that a spectrum formed by them, even when the slit before the prism is made very narrow, does not seem to be made up of separate strips of light placed side by side. Instead of this, each strip overlaps that next to it,

so that the spectrum looks like a band of light. Sometimes the light of a spectrum of this kind is so faint that its colors scarcely appear; generally, however, it is colored; in either case, it is called a **continuous spectrum**. The width of this spectrum depends on the size of the opening through which the light comes. If this opening is a slit, then the width of the spectrum depends on the length of the slit; provided that the apparent size of the object from which the light comes is considerable. But the spectrum of a star is narrow, whatever length the slit may have. The length of the spectrum depends on the shape of the prism, the material of which it is made, its distance from the place where the spectrum is examined, and the difference of refrangibility between the light at one end of the spectrum and that at the other. The spectrum formed by light sent out from any object is commonly called the spectrum of that object.

495. The spectrum of an ordinary flame is continuous; for the brightness of the flame depends on the small solid particles of soot which are burning in it, rather than on the hot gas in which they float. When a flame of this kind is bright enough, its spectrum is dark red at the end formed by the least refrangible light, and gradually changes through various shades of red and orange to yellow in its middle portions. Beyond the yellow portion, the spectrum continues to change by degrees through different tints of green and blue. But ordinary flames are apt to send out more yellow and red light in proportion to that which is green and blue than a beam of sunlight does. The spectrum of sunlight, at that end formed by the most refrangible light, has a violet color; so that it seems as if it were on the point of becoming red again when it ends. Certain chemical effects, which can be produced more readily in blue and violet than in red or even in yellow light, can also be produced beyond the violet end of the spectrum. It appears, then, that the spectrum does not absolutely end where it ceases to be seen, but that there are certain rays, which have been called invisible actinic rays, more refrangible than those which form violet light. In like manner, certain effects of

heat, which can be more easily produced in red than in blue light, can be produced beyond the red end of the spectrum. This gave rise to a theory that there are three spectra partly overlapping each other, only one of which could be seen; but recent researches have shown that there are serious objections to this theory. The proper explanation of the matter has not yet been fully settled.

496 The spectrum of sunlight is not perfectly continuous, when formed by a sufficiently narrow slit; it is crossed by numerous **dark lines**. To account for these lines, we must consider the properties of gases with respect to light. Under certain conditions, an incandescent or phosphorescent gas may send out light which forms a continuous spectrum; under other conditions, its spectrum may be discontinuous; in other words, when a sufficiently narrow slit is used, the spectrum may be made up of separate strips of light, usually called bright lines. Now when light which would otherwise form a continuous spectrum comes through a gas on its way to the prism, this gas being not too hot compared with the body to which the continuous spectrum belongs, a curious effect is produced. The continuous spectrum is crossed by dark lines at just those places where bright lines would have been seen if the spectrum of the gas itself, in an incandescent state, had been observed instead of the spectrum of the body behind the gas. That is, a gas absorbs light of the same refrangibility with that which it is itself capable of sending out. A gas may be bright enough to have a discontinuous spectrum of its own, and may yet absorb particular kinds of light from a brighter object behind it.

497. Now whatever the Sun may be made of, the spectrum of its photosphere (32) is continuous, while the gases enclosing the photosphere, and forming the various portions of the Sun's atmosphere, absorb particular kinds of the light which the photosphere sends out. For instance, there is much hydrogen in the Sun's atmosphere. One of the bright lines of the spectrum of incandescent hydrogen is of a particular shade of red; and in the spectrum of sunlight there is a

strong dark line just at the place where that particular shade of red would come in a perfectly continuous spectrum. The other bright lines of the spectrum of hydrogen also have dark lines answering to them in the spectrum of the Sun; and so it is with many other kinds of matter besides hydrogen gas. A metal may be made to give a spectrum of bright lines by passing strong electric sparks between the ends of wires made of the metal. In this way we learn what the spectrum of a metal would be if the metal were gaseous instead of solid; and when we find in the spectrum of sunlight dark lines answering to the bright lines of any metallic spectrum, we conclude that the metal to which that spectrum belongs is in the Sun's atmosphere, and reduced to a gas by the heat around it.

498. The spectrum formed by light which has passed through certain gases and liquids shows **dark bands**, broader than the dark lines just mentioned. Any band of this kind shows that light of many degrees of refrangibility differing little from each other has been absorbed by the gas or liquid lying between the prism and the body which is giving out light. Having learned what particular bands or lines any medium produces in the continuous spectrum of an object behind it, we can then tell by the appearance of a spectrum whether that medium lies between us and the body which gives out the light we are examining. In these ways, and in others like them, we can study the chemical properties of bodies at a distance from us (9). Occasionally, too, we can learn something of their density and heat; for the lines of spectra change their width and appearance to some extent according to the density and heat of the gases to which these lines are due. The opinions which now prevail respecting the structure of the fixed stars (95) depend on observations of this kind. For instance, the hydrogen lines in the spectrum of Sirius are dark and wide; hence greatly condensed hydrogen is thought to abound in the atmosphere of Sirius.

499. When a line appears in any spectrum very near the

place where such a line would have been expected to appear, but not exactly in that place, the explanation of the appearance usually given is that the body producing the observed line is in motion with respect to the observer. Thus, a hydrogen line in the spectrum of Sirius has been thought to be a little less refrangible than the corresponding line in the spectrum of the Sun ; and this appearance has been thought to show that the distance between Sirius and the Solar System is rapidly increasing (94). But this explanation is thought to be incorrect by some of the few people who know enough to make their opinions on the subject worth having. Those who have not thoroughly studied the science of optics cannot understand the arguments in favor of the explanation just mentioned or those against it ; although they may easily fancy that they understand them.

500. Lines in the spectrum of the Sun, or in the spectra of its prominences, are sometimes seen curiously bent one way or the other ; and these observations, too, are thought by some, but not by all, astronomers to show that certain movements take place in the Sun's atmosphere (70).

501. The name of **spectroscope** may be given to any instrument intended to be used in forming and studying any kind of spectrum. The only indispensable part of a spectroscope, then, is a prism or some other contrivance for dispersing light. But the spectroscopes most frequently used have many other parts. One of these parts is a slit placed before the prism, and so made that it may be opened or closed as far as seems desirable. Before the prism there are also lenses intended to put the light which comes to the instrument into the form of parallel pencils. Behind the slit and prism is a little telescope with which the spectrum may be examined. There must also be some measuring apparatus for determining the place of each line in the spectrum with respect to other lines either of the same or of another spectrum. In studying the spectra of stars, a piece of glass called a cylindrical lens is used to make the spectrum wider than it would otherwise be.

502. When a long spectrum is wanted, a considerable number of prisms must be used. In going through these prisms, the general direction of the light is often much changed. In fact, the beam of light which enters the instrument is sometimes carried round in a ring through several prisms, until it has got back nearly to its old direction; then reflected and sent the other way through the same ring of prisms before it is allowed to come out into the tube where it is observed. By apparatus of this kind, the light may be refracted twenty or thirty times, becoming more and more dispersed at each refraction. If it is so much dispersed, only a little of the spectrum it forms can be seen at once. This makes it necessary to contrive means for bringing any particular part of the spectrum into view, and at the same time setting the prisms so that they may act to the best advantage on that particular part. A spectroscope fitted with suitable contrivances for doing this is called an automatic spectroscope.

503. When the shape of one of the Sun's prominences is to be observed by means of a spectroscope (66), the slit is opened enough to allow the whole prominence to be seen through it (492), and that part of the spectrum which contains some particular line in the spectrum of the prominence is brought into view. The red line of hydrogen (497) is usually chosen for this purpose. There is now a red image of the prominence in view, and also a confused spectrum of sunlight reflected from the Earth's atmosphere, or from its liquid and solid contents. But this confused spectrum has been made fainter by the dispersion of its light in its passage through the prisms of the spectroscope; while as the red light of hydrogen is all of one kind, it is merely separated farther and farther, by its passage through the prisms, from the rest of the light sent out by the hydrogen and by the other kinds of matter in the prominence. The more the spectroscope disperses light, therefore, the fainter is the light among which the prominence appears, compared with the light of the prominence itself. Hence, if we have a sufficiently

powerful spectroscope, we may easily see the shape of any part of the chromosphere.

504. During a total eclipse of the Sun, a spectroscope used without a slit will give several distinct and differently colored images of the brighter part of the light then seen around the Sun; for the spectrum of this light is discontinuous (492, 496), the Sun's atmosphere being largely made up of incandescent gases.

505. For astronomical purposes, spectroscopes are usually attached to telescopes. The eye-piece of a telescope is taken off when the spectroscope is to be used with the telescope, and the spectroscope, with its various lenses, is put in the place of the eye-piece. This combination of telescope and spectroscope has been called a telespectroscope; but this name is little used.

506. A direct vision spectroscope is one in which the light is dispersed without much change in its general direction (489).

# CHAPTER XII.

## PRACTICAL ASTRONOMY.

507. The practical work of all astronomers must chiefly consist in measuring angles; for we can study celestial objects only by means of our eyes, and can never come near enough to them to handle, measure, and weigh them as we do the terrestrial objects which we study. All that we can do in the measurement of celestial objects is to measure visual angles (452) between different points of the same object, or between a point in one object and a point in another.

508. The great use of the magnifying power of a telescope is to enable us to measure, more accurately than we otherwise could, the small visual angles between points nearly in a line with each other as seen from the Earth. The fixed stars, which include most of the celestial objects usually in sight (21, 26), are made to appear smaller, rather than larger, by the use of telescopes in observing them (80). But the visual angles between them may be magnified, as we have seen (89, 91).

509. The distance of any object from the Earth can only be determined by observations of parallax (357, 450); and accurate observations of parallax consist in the measurement at different places or times of certain small visual angles. The distance between any two celestial objects cannot usually be known unless we first know the distance of both of them from the Earth; and never can be known if we cannot learn the distance of either of them from the Earth. Our knowledge of the size and mass of any celestial object also depends on our knowledge of its distance. All astronomical measurements, then, must be obtained by calculation from measured visual angles.

510. It is found convenient in practice to measure many visual angles by finding the time during which bodies change their directions from the place of observation by amounts equal to the angles which are to be measured. We have seen, for instance, that the apparent diameter of the Moon may be measured by the time required for the passage of a thread across the disk of the Moon (484).

511. It is also frequently found convenient to substitute arcs for visual angles (410). We usually regard ourselves as living beneath a dome-shaped surface which we call the sky (259). In the practical work of astronomy, we take advantage of this natural way of looking at the universe, in order more readily to keep in mind what angles we are considering. But, for the sake of accuracy, we speak of the celestial sphere rather than of the sky. This celestial sphere has its centre wherever the observer is, or supposes himself to be. How far off from him its surface is placed is a matter of no consequence, so long as all parts of that surface are understood to be equally distant from the observer's place. A celestial sphere a foot in diameter, with its centre at a point about the middle of the observer's eye, will answer the purposes of astronomy as well as one large enough to take in all the known universe. But perhaps the easiest way of understanding the celestial sphere is to regard its surface as beyond every object that can be discovered.

512. Wherever we place this surface, we regard all the celestial objects as projected upon it (270), the point of sight being always at the centre of the sphere. We may then replace the visual angle between two objects by the arc of a great circle of the celestial sphere (412), passing through the projections of the two objects. The **apparent distance** between the objects is accordingly the amount of rotation answering to the arc thus defined. This will be plain to any one who takes the trouble to get a clear understanding of the meaning of great circles, arcs, and angles. A less accurate way of explaining apparent distances on the celestial sphere, but one which makes it easier to get a rough notion of them,

is that the apparent distance between two stars is the fraction of the whole distance round the sky formed by a line drawn along the sky as directly as possible from one star to the other.

513. In order to measure arcs upon our imaginary celestial sphere, we find it well to choose certain points and circles upon its surface from which we may afterwards measure. Our choice will evidently depend to a great extent on the place where the centre of the sphere is supposed to be. Three suppositions with regard to this centre are in common use by every astronomer.

514. First, the centre of the celestial sphere may be regarded as at some point near the surface of the Earth, this point, for any particular observation, being in the instrument with which the observation is made. Secondly, in many calculations, it is convenient to suppose the Earth's centre (157) to be the centre of the celestial sphere. When we speak of the **geocentric place** of any object, we mean the place of its projection on the surface of a celestial sphere, the centre of which is at the Earth's centre. Thirdly, in other calculations, the most convenient centre for the celestial sphere is the centre of the Sun. The **heliocentric place** of any object is the place of its projection on the surface of a celestial sphere with its centre at the centre of the Sun. When the **place**, or the **apparent place**, of an object is spoken of by astronomers, they often mean its geocentric place; at other times, they mean the place of its projection on the surface of a celestial sphere with its centre somewhere on the Earth's surface; the exact place of this centre depending on the place and kind of the observations which are under consideration. It usually makes little difference in the place of a celestial object whether we suppose the centre of the celestial sphere to be in one terrestrial place or another.

515. We can now give more exact meanings than we previously could to some of the astronomical terms which we have had to use. The **zenith** and **nadir**, for example, are the points where the surface of the celestial sphere is pierced

by the vertical line (252) which passes through the point chosen for the centre of the sphere. The nadir is that one of these points which lies in the same direction with the Earth's centre from the centre of the celestial sphere; the zenith lies in the opposite direction. Hence, if we place the centre of the celestial sphere at the centre of the Earth, we can have no zenith or nadir.

516. The **horizon** is the great circle of the celestial sphere formed by the intersection of its surface with a plane passing through its centre and perpendicular to the vertical line (412) The plane of the rational horizon is parallel to the plane of the horizon just described, and passes through the centre of the Earth (264). No two places can agree in the planes of their horizons; but if they are in the same vertical line, the planes of their rational horizons will be the same. The zenith and nadir are the poles of the horizon (412).

517. The **meridian** is the great circle of the celestial sphere formed by the intersection of its surface with a plane containing both the vertical line and the Earth's axis. Hence different places may have different meridians; but two places, equally far from the Earth's centre, may agree in the planes of their meridians, although their vertical lines must differ. The intersection of the meridian plane of any terrestrial point with the Earth's surface may be called the terrestrial meridian of that point. But in fact, its meridian on the celestial sphere is the meridian by which its longitude is reckoned, as we shall see.

518. The **prime vertical** is the great circle of the celestial sphere formed by the intersection of its surface with a plane containing the vertical line, and perpendicular to the plane of the meridian.

519. The points where the meridian crosses the horizon are the north and south points; those where the prime vertical crosses the horizon are the east and west points (36, 156, 282).

520. All great circles of the celestial sphere which contain the vertical line are **vertical circles.** The angle between the planes of any two vertical circles is a **difference of azimuth**;

and the arc of the horizon lying between these planes is an arc answering to this angle, and signifying the same amount of rotation (410). The **azimuth** of any object is the angle between the meridian plane and the plane of the vertical circle passing through the projection of the object on the surface of the celestial sphere. In other words, the azimuth of any object is the arc of the horizon lying between the north or south point (as the case may be) and the point where the horizon is crossed by the vertical circle on which lies the projection of the object. **Amplitude** is the difference of azimuth between the east or west point and any object which is rising or setting.

521. The zenith and nadir are points belonging to every vertical circle, and accordingly have no azimuth; or, if we choose, we may consider them as belonging to any particular vertical circle, and as having the same azimuth with any given point in that circle. Any point in the prime vertical has an azimuth of 90°.

522. Since all points in any particular vertical circle have the same azimuth, we must know more than the mere azimuth of a point before we can settle its place on the celestial sphere. If a line is drawn from the centre of the sphere to the point the place of which is to be determined, the angles between this line and the vertical line are the **zenith distance** and the **nadir distance** of the point. Either of these angles will serve our purpose, but the zenith distance is the angle most frequently used. The arc answering to zenith distance belongs of course to a vertical circle, and reaches from the zenith to the point the place of which is to be determined. The arc of the same circle extending from this point to the horizon is the **altitude** of the point. When we know the azimuth and zenith distance of a point, or its azimuth and altitude, we can find the point on the celestial sphere if we are told where to begin reckoning azimuth. For instance, if the altitude of a point is 45° and its azimuth 90°, it must be in the prime vertical, half-way from the horizon to the zenith. But there are two such points, one east and the other west of

the zenith. If we are told, however, to begin reckoning azimuth at the south point, and go towards the north through the west, we know that the point we are to find is that west of the zenith. The azimuth of the other point would be 270° instead of 90°.

523. When altitudes are reckoned from the horizon to points below it, the negative sign of algebra is placed before the figures denoting altitude. Thus any point the altitude of which is —40° has a zenith distance of 130°; for the zenith distance of the horizon is 90°, and the point is 40° farther than the horizon from the zenith.

524. The Earth's rotation constantly changes the places of all the circles just described among the projections of the celestial objects; but if we choose, we can regard the circles as stationary and the projections as having a retrograde movement across them (125). This movement is commonly called the **diurnal movement** of the stars and other celestial objects. The diurnal movement, as observed from either of the Earth's poles, is only a movement in azimuth (281); but as observed from any other terrestrial place, it is a movement both in azimuth and in altitude.

525. One of the various meanings of the word **transit** is passage across a circle of the celestial sphere (328, 361). We speak, for instance, of the transits of stars over the meridian or over the prime vertical; and instruments meant for observing the times at which these transits happen are called transit instruments. Meridian transits are also called **culminations**. Every star crosses the meridian twice while its diurnal movement carries it once round the Earth. These two culminations are called the **upper** and **lower** culminations of the star. If it is one of the stars which never set at the place where it is observed (124, 285), both its culminations will be in view; otherwise its lower culmination will take place below the horizon.

526. If we now consider the centre of the celestial sphere to be at the Earth's centre (514), so that we can have no vertical line, the line of the Earth's axis will naturally be the

chief line to be used in our measurements. The points where it pierces the surface of the celestial sphere may be called the **celestial poles**, or simply the **poles**. The great circle of the celestial sphere of which these points are the poles (412) is the **celestial equator**, or the **equinoctial**; but it is usually called simply the **equator**. Its plane is evidently the same as the plane of the terrestrial equator. The great circles of the celestial sphere which pass through both poles are so often spoken of as **meridians** that this name for them cannot be called incorrect, although, at the outset of works on practical astronomy, they are usually called **hour circles**, or **circles of declination**. They differ from the meridians already described (517) in not being carried about by the Earth's rotation. The angle between the planes of the meridians of any two terrestrial places is the **difference of the longitudes** of those places, as we learn by the study of geography; the angle between the planes of two hour circles is called a **difference of right ascension**. The angle between two lines, one of which is the intersection of the plane of the equator with that of the meridian of some terrestrial place, while the other passes through that place and through the Earth's centre, is the **latitude** of the place. The angle between two lines, one of which is the intersection of the plane of the equator with that of an hour circle, while the other passes through some point in that circle and through the centre of the celestial sphere, is the **declination** of the point. The meanings of longitude and latitude, right ascension and declination, are more easily understood when they are explained by means of arcs than when explained by means of angles; but it must be remembered that they are not distances. The latitude of a city, for instance, is not the distance in miles between some point in that city and the nearest point on the equator; it is the angle between the vertical lines of these two points, or the fraction of a meridian lying between these vertical lines, no matter how far from the Earth's centre we place the surface of the sphere on which the meridian is supposed to be drawn. In reckoning latitude

accurately, we take into account the fact that vertical lines do not always pass exactly through the Earth's centre (253). It is easy to see that the declination of a star is not a distance, because we cannot measure in miles on the celestial sphere as we can upon the Earth; when we say that a star is in 20° north declination, we obviously mean that the arc of the hour circle passing through the projection of the star, and measured northwards from the equator to this projection, is one-eighteenth of the whole circle, whether the extent of that circle is considered as only a few feet, or as millions of times greater than the distance of the most remote stars from the Earth (410). For the whole circle contains 360°; and 20 is $\frac{1}{18}$ of 360.

527. North polar distance (which, like zenith distance, is merely angular distance) may be used in stating the places of stars when it is thought more convenient than declination. Thus, the north polar distance of a star is 130° if the star is in 40° south declination, or, as it may be expressed, if the declination of the star is —40° (523).

528. Suppose that the place of the whole celestial sphere, with its poles, equator, and hour circles, as just described, is changed by rectilinear motion (408), so as to carry its centre to some place near the surface of the Earth. The sphere will now coincide with the celestial sphere of that place. The meridian of the place, which may be called the **local meridian**, will be brought by the Earth's rotation to coincidence with one after another of the hour circles (or celestial meridians); or, if we please, we may consider the hour circles as having a diurnal movement (524). If the place selected is one of the Earth's poles, the equator will coincide with the horizon and the vertical line with the axis. If it is a place on the Earth's equator, the poles will coincide with the north and south points, and the equator will pass through the zenith.

529. Any change in the right ascension and declination of celestial objects produced by the shifting of the celestial sphere in the manner just supposed is an effect of parallax (357). The most usual meaning of **parallax** is the angle

between the lines pointing to an object from the Earth's centre and from the place for which the parallax of that object is to be determined. If the object is in the zenith it will have no parallax; if on the horizon, its parallax will be as great as possible. The parallax of an object on the horizon is its **horizontal parallax**. If the place of observation is on the Earth's equator, it will be as far as any terrestrial place from the centre of the Earth (159). Hence the horizontal parallax of an object is greatest when the object is viewed from some place on the Earth's equator; this parallax is **equatorial horizontal parallax**, and is often what we mean when we use the word parallax by itself. The comparison of the apparent places of an object observed at about the same time in different parts of the Earth will show the difference of its parallaxes at the stations from which it was observed. If this difference is noticeable, we may derive from it the equatorial horizontal parallax and the distance of the object.

530. The **hour angle** of any celestial object is the angle between the plane of its hour circle and that of the local meridian, at some particular time and place.

531. When the centre of the Sun is taken as the centre of the celestial sphere, the ecliptic is usually considered to be the principal circle of that sphere. We are now able to define the **ecliptic** more exactly than we could before (322). It is the great circle formed by the intersection of the plane of the Earth's orbit (139, 143) with the surface of the celestial sphere. The **poles of the ecliptic** are the points where the surface of the celestial sphere is pierced by a line drawn through its centre perpendicular to the plane of the ecliptic. This line may be called the axis of the ecliptic. The great circles passing through both poles of the ecliptic are called **circles of latitude**, and the angles between their planes are called **differences of longitude**, while arcs of these circles of latitude extending either way from the ecliptic, or the angles answering to these arcs, are called **latitudes**. Celestial longitudes and latitudes differ from the terrestrial angles

of the same names in being measured on the ecliptic and the great circles passing through the poles of the ecliptic, instead of on the equator and the meridians.

532. We may now again consider the celestial sphere to be shifted by rectilinear motion so that its centre may be brought from the centre of the Sun either to the Earth's centre or to some part of its surface. The sphere will then coincide with the celestial sphere of the place to which its centre is thus removed. The great circle of the sphere called the ecliptic will lie in a plane parallel to that which we have hitherto called the plane of the ecliptic (139), if not actually in that plane. This change of plane, if any occurs, will make little difference in the latitudes of the stars, or of any celestial objects except those near the Earth. Even the longitudes of the stars will not be noticeably altered by the change, owing to their great distance, which makes the parallax of even the nearest of them hardly perceptible; the **parallax of a star** being the angle between the lines drawn from it to the Sun and to the Earth. But the longitude of any object between the Sun and the Earth must be changed 180° when the centre of the celestial sphere is carried past it. Suppose, for instance, that the centres of the Sun, Mercury, the Earth, and Mars, are at some one time in the plane of the ecliptic, Mercury being between the Sun and the Earth, and the Earth between Mercury and Mars. Then, if the Sun's centre is the centre of the celestial sphere, the longitudes of Mercury, the Earth, and Mars will all be the same; if the celestial sphere is shifted so as to bring its centre to coincide with that of the Earth, this change will leave the longitude of Mars as it was, and will place Mercury in the opposite longitude, where also the Sun will be placed. The longitude and latitude which, when taken together, determine the heliocentric place (514) of any body, are its **heliocentric longitude** and **latitude**; and its geocentric place may be shown either by its **geocentric longitude** and **latitude**, or by its **right ascension** and **declination**. As we have seen, geocentric and heliocentric latitude may differ somewhat, and geocentric and heliocentric

longitude considerably. When the centre of the sphere on which longitude and latitude are reckoned is supposed to be at the Earth's surface, the longitudes and latitudes of objects sufficiently near the Earth will differ slightly by the effect of parallax (529) from their geocentric longitudes and latitudes.

533. In reckoning azimuth, right ascension, or longitude, we must choose some point for the beginning of our reckoning. The point chosen for this purpose in reckoning azimuth is either the north or the south point of the horizon (522). Right ascension and longitude begin at the vernal equinox, which we can now define more exactly than we previously could (323). Since the planes of the ecliptic and equator do not coincide and both pass through the centre of the celestial sphere, they must intersect each other in a straight line, called the **line of the equinoxes**, which pierces the surface of the celestial sphere in two opposite points, where the equator and ecliptic cross each other. The Sun's centre is projected at or near one of these points at the time of the vernal equinox (301); hence the point itself is often called the **vernal equinox**, although some writers prefer to call it the first point of Aries.

534. The **right ascension** of any object may be denoted by the arc of the equator beginning at the vernal equinox and following the course of any thing supposed to have direct motion along the equator to the point where it crosses the hour circle passing through the object. As there are two of these points, that point is chosen from which the declination of the object is measured; in other words, the point which is less than 90° of a great circle from the object.

535. The **longitude** of any object is measured from the vernal equinox along the ecliptic, following the course of any thing supposed to have direct motion in the ecliptic, to that point crossed by the circle of latitude passing through the object, and from which the angular distance, or latitude of the object, is less than 90°.

536. A few illustrations will be of service in clearing up the meaning of these statements. Let us suppose that at

some moment when the vernal equinox has just come to coincidence with the west point of the horizon, the centre of the Moon has just come to its upper culmination (525). The line of the equinoxes is now perpendicular to the plane of the local meridian (528), and this local meridian, therefore, has the equinoxes for its poles (412). Hence, if any great circle passing through the equinoxes is considered as cut in halves by the line of the equinoxes, either half of it will now be cut in halves by the local meridian; so that one-fourth, or 90°, of the whole circle will lie between either equinox and either of the points where the circle crosses the local meridian (just as one-fourth of the local meridian itself lies between either pole and the equator). Both the equator and the ecliptic are great circles passing through the equinoxes. Hence 90° of the equator and likewise 90° of the ecliptic lie at this moment between the west point of the horizon and the local meridian. The local meridian coincides with the meridian (or hour circle) of the Moon's centre; and it also coincides with the circle of latitude passing through the Moon's centre. For the poles of the equator always lie on the local meridian; and when the equinoxes are on the horizon, the poles of the ecliptic must also lie on the local meridian; or else each of these poles would be nearer one equinox than the other. We must measure right ascension and longitude the contrary way from that in which celestial objects are carried by their diurnal motion. As we have seen, this will make the right ascension of the Moon 90°, and its longitude also 90°.

537. If the Sun is at this time just passing its lower culmination (525), its right ascension and geocentric longitude are 270°; for although it is, like the Moon, in the plane of the local meridian, we must not end our measurements of its right ascension and longitude at the points where we stopped in the example already given. If we measured from the Moon's centre either way along the local meridian towards the Sun, we should not reach it until we had passed through one of the poles of the equator, and likewise through one of

the poles of the ecliptic. We must therefore (534, 535) measure three-quarters of the way round either the equator or the ecliptic, beginning at the vernal equinox, in order to get the right ascension and longitude of the Sun; and three-quarters of 360° is 270°.

538. If we wish to find the declination of the Moon at its upper culmination, we must measure the angle between two lines drawn from the centre of the sphere, one to the Moon's centre, and the other to the nearest to the Moon of the two points where the equator crosses the meridian. In the example already given, let us suppose this angle to be 20°; or, which amounts to the same, let us suppose that the arc of the local meridian, one end of which is at the projection of the Moon's centre and the other at the nearest point of the equator, is one-eighteenth of the whole meridian. Let us now inquire whether the Moon is north or south of the equator, and also what its geocentric latitude must be.

539 Regarding the equinoxes, when they are on the horizon, as the poles of the local meridian, we may measure the angles between the planes of great circles passing through the equinoxes by means of arcs of the local meridian, just as we measure angles between the planes of meridians or of hour circles by means of arcs of the equator. Now the angle between the planes of the equator and ecliptic is about $23\frac{1}{2}°$ (166). Hence the arc of the local meridian lying between the equator and ecliptic is $23\frac{1}{2}°$, or rather less than one-fifteenth of the whole meridian, whenever the equinoxes are on the horizon. Moreover, if the vernal equinox is on the western horizon, the first half of the ecliptic, measured from the vernal equinox, lies north of the equator (324). Now the plane of the Moon's orbit is inclined only about 5° to the plane of the ecliptic (176). Accordingly, the arc of the local meridian between the projection of the Moon's centre and the ecliptic can never be large; it will be at its largest when the Moon culminates, and, at the same time, the points where the projection of its orbit crosses the ecliptic come to the horizon. Even then the arc will be only about 5°; just as the arc of

the local meridian between the equator and the ecliptic is only about $23\frac{1}{2}°$ when the equinoxes are on the horizon, and is less at other times.

540. It seems, then, that in the case we have supposed, the Moon's declination is 20° north and not south of the equator; for as the ecliptic crosses the meridian about $23\frac{1}{2}°$ north of the point where the equator crosses the meridian, the Moon would be about $43\frac{1}{2}°$ from the ecliptic if it were 20° south of the equator. The Moon's latitude is evidently about $3\frac{1}{2}°$ south. These facts may be also stated as follows: At the time of our supposed observation the Moon's right ascension is 90° and its declination +20°; its longitude is 90° and its latitude $-3\frac{1}{2}°$. If we wish to state its geocentric place accurately, we must calculate the effect of parallax in altering its declination and latitude. Its right ascension and longitude will still be 90° each. In other words, it will remain in the plane of the local meridian if the centre of the celestial sphere is moved to the Earth's centre; for the Earth's centre is itself in the plane of the local meridian.

541. The longitude and right ascension of a celestial object will not usually be equal to each other, as in the examples just given. But the spherical triangle having its angles at the object, one pole of the equator, and one pole of the ecliptic, will enable us to determine the longitude and latitude of the object from its right ascension and declination, or these last from its longitude and latitude. By means of similar trigonometrical calculations, if we know the azimuth and altitude of an object, and those of the vernal equinox, we can determine the right ascension and declination, as well as the longitude and latitude, of the object. The place of the vernal equinox, however, cannot be directly observed; it has to be found from an extensive series of observations of the Sun and stars, as will presently be shown. When an object is crossing the meridian its declination is merely the difference between its zenith distance and the latitude of the place of observation. It must be remembered that the words longitude and latitude are used in different senses according to their appli-

cation to terrestrial or celestial objects (531): but both kinds of longitude and latitude are measured on the celestial sphere (517).

542. For instance, the **latitude of a terrestrial place** may be regarded as the arc of the local meridian lying between the zenith and the equator (526). In other words, it is the zenith distance of the point where the local meridian crosses the equator. Hence terrestrial latitudes may be learned from the declinations of stars, just as declinations may be learned from terrestrial latitudes. If the declination of a star is 3° north, and it crosses the meridian 12° south of the zenith, then the latitude of the place of observation is 15° north. When accuracy is required, we must take refraction into account (262). All this becomes evident when we remember that at either pole of the Earth the equator coincides with the horizon and one of its poles with the zenith; while this pole approaches the horizon as we go farther towards the equator. It also appears that the altitude of the pole is equal to the zenith distance of the nearest point on the equator, and hence to the latitude of the place of observation: for the arc of the meridian from the pole to the equator is 90°, and the arc of the meridian from the zenith to the north point of the horizon is also 90°. Hence if we take from each of these arcs the arc between the zenith and the pole, the remainders will be equal; one of them being the zenith distance of the highest point on the equator, and the other the altitude of the pole. The zenith distance and the altitude of the pole may be found pretty accurately by observations of a star near the pole at both its culminations, even without any knowledge of its declination. We may thus obtain the latitude of some terrestrial place. This latitude may be used in determining the declinations of stars, and may itself be corrected by the comparison of a sufficient number of observations dependent on it.

543. In determining terrestrial longitudes, we make use of the Earth's rotation to measure our angles, and express these angles in time instead of expressing them in arc (405). The

rotation of the Earth is a movement more nearly uniform (120) than any other which we know of. Accordingly, if meridians could be drawn so as to be visible on the celestial sphere, the best possible clock for us to use would be the Earth itself. The local meridian of any particular place would answer for the hand of the clock, and the hour circles for the marks on its dial-plate. This clock, however, would not keep time with the Sun nearly enough for ordinary use (310, 311), although mean time clocks could be regulated by means of it.

544. In practice, when we wish to use the Earth as a clock, we have to place some kind of pointer in the plane of the local meridian to serve for a hand, and then use the stars for marks on the dial-plate. The line of sight through a telescope is the most accurate pointer we can use. But since the apparent movements of the stars are rendered slightly variable by the various real movements of the Earth about its centre (165), and since, moreover, the stars do not keep their places among each other (93), our observations of their transits do not directly measure the passage of time as accurately as is desirable. We can find, however, by calculation from these observations, the moments when the local meridian agrees with the meridian passing through the vernal equinox. The interval between one of these moments and the next but one is called a **sidereal day**. Since the vernal equinox is no actual object, but merely an imaginary point (533) determined by calculation, it follows that we might arrange our calculations so as to divide time into sidereal days of exactly equal length. But we could not be sure, after all, that one sidereal day would be exactly equal to another, unless we knew the rotation of the Earth to be a perfectly uniform movement; and probably it is not perfectly uniform. Astronomers have not thought it worth while to attempt to make all sidereal days exactly equal in length, but have contented themselves with making sidereal days much more nearly of equal length than are the days measured by the best artificial clocks. The place of the vernal equinox must be reckoned in such a man-

ner that it may nearly coincide with the actual place of the projection of the Sun's centre on any of the occasions when the Sun is actually passing through the plane of the equator from south to north. If the vernal equinox were regarded as fixed with respect to any stars the proper motions of which (93) are too small to be perceptible, it is obvious that the Earth's precessional movement would soon carry the equator away from this fixed equinox, while the ecliptic would also be gradually carried away from it by the change in its plane (166). We might, however, regard the equinox as having a perfectly uniform retrograde movement along the celestial equator, without making its place very different from that indicated by observations of the Sun, at any given time between the earliest and the latest recorded astronomical observations. But in practice, we regard the retrograde movement of the equinox, and hence the length of the sidereal day, as slightly variable.

545. We must now distinguish between two points called the **mean** and the **true** equinox. The mean equinox retrogrades at a rate which is meant to be proportional to that of the Earth's precessional motion, nutation being disregarded. The precessional motion is known to be very nearly, but not quite, uniform; hence, if we reckoned sidereal days by the culminations of the mean equinox, these days would be almost exactly equal. It is considered best, however, to reckon sidereal days by the culminations of the true equinox, in calculating the place of which, nutation, as well as precession, is taken into account. This makes the sidereal day slightly more variable than it would be if nutation were neglected; but the variation, as has just been said, is, after all, much smaller than the variations in the rates of the best time-pieces ever constructed. Since its amount may be calculated whenever we wish to compare one interval of time with another as accurately as possible, the uncertainty of our measurements of time is in fact nothing more than our uncertainty with regard to the uniformity of the Earth's rotation. The true equinox itself is not always precisely coin-

cident with the point of the equator crossed in March by the Sun's centre.

546. In the course of a single day, the want of strict uniformity in the lapse of sidereal time cannot become perceptible. We may accordingly assume that the diurnal motion (524) of the vernal equinox is perfectly uniform between any two of its successive upper culminations. During this interval, it moves through a whole circle of the celestial sphere, or through an angle of 360°. The sidereal day is divided into 24 **sidereal hours**; each of these into 60 **sidereal minutes**, and each sidereal minute into 60 **sidereal seconds**. Hence, in one sidereal hour, the vernal equinox moves through $\frac{1}{24}$ of the circle, or 15°; and, consequently, if two terrestrial places differ 15° in longitude (526), the local meridian of one place will coincide with the meridian of the vernal equinox one sidereal hour before the coincidence of the local meridian of the other place with the meridian of the vernal equinox. In like manner 15′ answer to one sidereal minute, and 15″ to one sidereal second.

547. It appears from this that if a clock at each of two terrestrial places is regulated to such a rate that it will count twenty-four hours in one sidereal day, and if the hands of each clock are set so as to point, when the vernal equinox comes to its upper culmination on the local meridian, to any hour which may be agreed upon, the **difference of time** between the clocks answers to the **difference of longitude** between the places. In fact, the difference of time between the clocks is the angle which their hands would make with each other if these hands were put on the same dial; provided that we suppose each clock to have only one hand, going round its dial only once in each sidereal day. The addition of other hands does not alter the fact that every ordinary clock measures time by measuring angles Sidereal clocks and chronometers are considered to be either fast or slow, unless the time shown by them when the vernal equinox comes to its upper culmination on the local meridian is exactly 0 hours, if the dial-plate shows twenty-four hours, or exactly

12 hours if the dial-plate is made like that of a common clock, so that the hour hand goes round it once every twelve hours. In using sidereal clocks to determine differences of longitude, we first determine their **errors**; that is, we find, by observations of the stars, how much the time shown by each clock differs from the local sidereal time. We then compare the clocks, which may now be done in a few minutes, however far from each other the clocks may be, provided that the places where they are are connected by telegraph. It is well, after making the comparisons, again to determine the error of each clock. In former times, before electric telegraphs were invented, it was necessary to carry chronometers backward and forward between the clocks in order to compare them; and as the clocks and chronometers had time to change their errors while the comparisons were going on, the work had to be repeated many times before satisfactory results could be reached. There are still other ways of comparing clocks; for example, the time of the occultation (362) of a star, or that of the eclipse of a satellite (364), may be observed in different places. The difference between the clocks, and the error of each clock, being known, we can tell what fraction of a sidereal day is required for the passage of the vernal equinox from the local meridian of one clock to the local meridian of the other. We can turn this fraction of a day into a fraction of a circle at the rate of 15° to the hour, or we can consider the hours, minutes, and seconds, shown by the clock, as angles, instead of considering them as intervals of time. Angles of longitude may thus be expressed in time instead of in arc (405). This is the ordinary practice; and while we are using only sidereal time it cannot lead to any confusion; but since we have mean time also to consider, we must be careful to know whether we mean an angle or a certain length of time, when we speak of an hour, a minute, or a second. The mean time (311) of one place differs from the mean time of another place by exactly as many hours, minutes, and seconds as there are in the difference between the sidereal times of the two places; for either

of these differences of local time (312) is in fact the angle between the planes of the meridians of the two places. But a second of mean time is longer than a sidereal second (311). Right ascensions, the reckoning of which is next to be explained, are at the present day almost always stated by means of sidereal time.

548. If the angle between the planes of the meridians passing through any two stars is stated in time, the resulting number of hours, minutes, and seconds will scarcely differ at all (546) from that number of hours, minutes, and seconds which denotes the sidereal time during which the local meridian of any place passes from coincidence with the meridian of one star to coincidence with the meridian of the other. If, then, we notice the exact sidereal times at which the two stars come to their upper culminations on any particular day, the **difference of these times** may be considered as the **difference of the right ascensions** of the stars. But if we wish to be precise, we may correct this determination by calculating the change in the apparent places (514) of the stars due to the various movements of the Earth between the times of the two culminations which have been observed. In practice, when the difference of right ascension between two stars is required, the stars must be many times observed at their culminations, and each observation corrected for such of the Earth's movements as have been learned. When all this has been done, any disagreement in the various results of the observations may be explained either by mistakes in the observations or by unknown movements of the Earth or of the stars themselves. If the observations are numerous enough, their mistakes will be likely to balance each other; so that if any disagreements between the results obtained are due to accidental errors, they too will balance each other in a particular way which will enable us to distinguish them from other disagreements due to unknown movements of the Earth and stars. These last disagreements are recorded for the purpose of future study of the movements which occasion them. In the present state of astronomical research they are always very small.

549. Work of this kind enables us to determine differences of right ascension between the stars which we observe. But it gives us no information about what are called **absolute right ascensions**, or the angles between the plane of the meridian of the vernal equinox and the planes of the meridians of particular stars. These must be found by frequent observations of the Sun. The time of the culmination of the Sun's centre is obtained by observing the culminations of both its preceding and following limbs (49), while the zenith distances of its northern and southern limbs give us the zenith distance of its centre. These observations, like those of the stars, must be constantly repeated and corrected. By combining them with observations of the stars, we learn the Sun's apparent path among the stars. From this we may determine the points which we are to regard at any given time as the mean and the true vernal equinox, in conformity with the plan adopted in our calculations (544, 545). We may also determine, from our observations of the Sun's course, to what great circle of the celestial sphere the name of the ecliptic should be given at any particular time. The angle between the planes of the equator and ecliptic, called the obliquity of the ecliptic, varies under the influence of nutation as well as in consequence of the fact that the Earth's course round the Sun cannot be considered as always lying in the same plane, even if the Sun's movements in space are disregarded (166). In practice, we calculate the place of the ecliptic from that of the equator; so that we may consider nutation, if we please, as changing the place of the ecliptic. When nutation is disregarded, the resulting ecliptic is called the **mean ecliptic**; and the angle between its plane and that of the equator is the **mean obliquity of the ecliptic**. Having decided on the places of the ecliptic and the equinox, we can determine the absolute places of the stars in longitude and latitude or in right ascension and declination. This work cannot be done once for all, but has to be continually begun again; for as we do not know all the movements of the celestial objects, we cannot calculate all

their effect beforehand. Still, we can calculate the future places of most celestial objects nearly enough to enable telescopes to be so pointed, at any particular time in the course of many years to come, that the objects may be seen through them (110) unless the view is obstructed by some opaque body.

550. The constant repetition of observations made to determine the right ascensions and declinations of the stars forms perhaps the chief business of astronomical observers. This work is monotonous and in itself uninteresting; it is very unlike that looking about for wonderful sights in which most people seem to fancy that all astronomers pass their time. But the results of the careful measurement of angles of right ascension and declination are of great interest and importance. They have been the means of making us acquainted with the complex precessional movements of the Earth, with the distances of several of the stars, and to some extent with the movement of the Solar System among the stars and the general movements of the stars among each other; although our knowledge of these last subjects is as yet scarcely begun. Besides all this, the observation of the places of stars is one of our means of information with respect to the speed of light. The movement of light, combined with the movement of the Earth in its orbit, alters the apparent place of a star in different ways at different times of year, for reasons which may easily be stated.

551. Every one knows that if he moves forward quickly in any direction, when the air is still, there seems to be a slight breeze blowing against him. If the air is not still, his movement will alter the direction with respect to him of any current of air through which he may be moving. For instance, if the wind is south, and blowing at the rate of ten miles an hour, while a traveller moves westward at the same rate, the wind appears to him as a south-west wind. If he moves less than ten miles an hour, the wind will seem to him more nearly south than west; if he moves more than ten miles an hour, it will seem to him more nearly west than south. If the

wind is very violent, and the traveller moving slowly, the wind will seem to him almost due south. Still, if he has any way of accurately measuring its direction with respect to himself, he may be able to notice that it is a little west of south.

552. If, instead of keeping on directly westwards, he gradually turns so as to face the south, the wind will seem more and more nearly due south ; and when he is facing exactly southwards, his own motion will not change the direction from which the wind seems to him to be coming, although it will make the wind seem a little stronger than it would seem if he stood still. If he continues to turn towards his left, he will presently be moving eastwards, and the wind will seem to be a little east of south. When he is moving exactly northwards, his movement may lessen the apparent speed of the wind, but will not alter its apparent direction.

553. If the traveller carries with him a straight tube, and always keeps it pointed so that the wind may blow directly through it, the tube must point due south only when it is carried exactly southwards or northwards. If the traveller moves at all towards the west, the tube must be pointed somewhat west of south ; and if he moves at all towards the east, the tube must be pointed somewhat east of south. The length of the tube will not make the least difference in the direction in which it must be pointed. If the wind apparently comes from the direction 1° west of south, the tube must be pointed 1° west of south whether its length is six inches or six feet. The exact angle which its direction makes with the plane of the meridian will depend on the rate at which the wind blows from the south compared with the rate at which the tube is carried westward or eastward.

554. Now since light is admitted to be a movement of some kind, this movement, when combined with the movements of the Earth, may be expected to make some slight difference in the direction in which any celestial object is seen by a terrestrial observer. For instance, if an observer watches a star at its upper culmination, he is carried by the Earth's

rotation across the line along which the star's light comes to him. Hence, in order to look at the star, he must look a very little east of the direction from him in which the star really is; and if he is looking through a telescope along a line in the plane of the meridian, the star will seem to pass that line a very little later than it would if light moved still faster than it does. But the speed of light is so great in comparison with that at which a terrestrial place, even one on the equator, is carried along by the Earth's rotation, that this change of direction, called the **diurnal aberration**, is too small to be accurately observed. It has been calculated from the speed which other observations have shown to be that of light. From these calculations it appears that a star seems to culminate about two hundredths of a second later by reason of this diurnal aberration than it otherwise would, provided it is on the equator, so that its diurnal motion carries it daily round a great circle of the celestial sphere, and that the observer is on the Earth's equator, where the diurnal aberration is greatest. Although the angle of the diurnal aberration of one star is the same as that of another, the time which the star takes in apparently moving through this or any other angle must increase with its declination; for the arc answering to this angle must be measured on a great circle of the celestial sphere, while the circles of diurnal motion of all stars not on the equator are small circles of the sphere, so that the stars seem to move slower the farther they are from the equator (124).

555. What is commonly meant by the **aberration of light** is due not to the Earth's rotation, but to its movement in its orbit. Its effect in changing the apparent place of a star is called **annual aberration**. The extent of the Earth's orbit is near five hundred and eighty millions of miles; so that as there are three hundred and sixty-five days in the year, we are carried along by the Earth's movement in its orbit at the rate of over one and a half million miles a day, while even if we are on the Earth's equator we are only carried some twenty-five thousand miles a day by its rotation. Light moves about

one hundred and ninety thousand miles in a second, so that in about eight seconds it moves as far as the Earth's movement in its orbit carries it in a day. Roughly speaking, the Earth's motion in its orbit is always perpendicular to the line from the Earth to the Sun; and this line lies in the plane of the ecliptic. Hence if the geocentric longitude of a star (532) differs 180° from that of the Sun, the Earth's motion in its orbit will carry it directly across the line along which the star's light comes to it; and the star's place will be changed as much as aberration can change it, which is of course only a little. This greatest angle of aberration, commonly called the constant of aberration, amounts to no more than 20″.5. It has not been fully settled whether there is any thing in the movement of light by which there may be produced an effect like that by which a breeze seems stronger when we walk against it (499. 552).

556. If a star is on the ecliptic, its aberration will merely make it seem to move back and forward on the ecliptic over an arc of about 41″ (20″.5 each way from the middle) in the course of a year. In other words, its aberration would be only aberration in longitude. But stars which are not on the ecliptic will have also some aberration in latitude. For instance, if a star is at one of the poles of the ecliptic (531), the line along which its light comes to the Earth is always perpendicular to the direction in which the Earth is moving; for the width of the Earth's orbit is too small to be considered in comparison with the distance of any star from the Earth. Hence a star at the pole of the ecliptic would always seem to be 20″.5 out of its place, and would go round that pole in a small circle in the course of the year. Its aberration would be wholly aberration in latitude; for it would always be brought by aberration towards the ecliptic from the place in which it would be seen if the Earth's movement in its orbit were stopped. But the change caused by aberration from one to another of its apparent places is only a change in longitude.

557. Any ordinary star has no aberration in latitude and

most in longitude when its longitude is the same as that of the Sun, or differs from the Sun's by 180°, as we have seen. It has no aberration in longitude and most in latitude when its longitude differs 90° from that of the Sun. But its aberration in latitude never amounts to the whole of the constant of aberration (555), so that its changes of apparent place, so far as they are due to aberration, carry it round a small ellipse, the major axis (145) of which is a line connecting the ends of an arc of about 41″, while the width of the ellipse increases with the star's latitude, but can never exceed 41″.

558. From the aberration of any star in longitude and latitude its aberration in right ascension and declination may be readily calculated.

559. There is a change in the apparent places of the stars, which, like aberration, is repeated every year in the same way. This change is due to **parallax** (532). It is so small that it has been discovered to alter the places of only a few of the stars, and its amount depends not on the speed of the Earth, as aberration does, but on the distance across the Earth's orbit. Hence when aberration is greatest, parallax is least. If the Earth is directly between a star and the Sun, the aberration of the star will amount to the full constant of aberration, while the star's parallax is nothing, because its direction from the Sun is the same with its direction from the Earth. This enables us to distinguish between effects of parallax and effects of aberration. But the largest parallax which has been discovered in any star is less than 1″; that is, no star is known to change its place as much as 2″ in the course of the year (1″ each way), so far as parallax is concerned. This shows that the nearest stars are over two hundred thousand times as far from the Sun as the Earth is (21), unless some stars, the parallax of which has never yet been studied, should hereafter be found to be nearer to us than those which are now thought to be the nearest.

560. The movement of a celestial object, combined with the fact that its light does not reach us instantaneously, may

make its apparent place differ from that in which we should see it if light moved more quickly than it does. This effect must be taken into account in reckoning the place of a planet, and is hence called **planetary aberration**. It may occur, of course, in the case of a star, but cannot be reckoned, as we know little about the distances and movements of stars.

561. When all the changes in the apparent places of stars which can be attributed to the known motions of the Earth have been allowed for, others often remain, as we have seen (548). That is, after allowing for precession, nutation, change of the plane of the ecliptic (166, 167), aberration, and parallax, we still find that the right ascensions and declinations of stars determined at one time do not agree exactly with those of the same stars determined at another time some years later. These disagreements are called **proper motions** of the stars in right ascension and in declination. They do not always continue with exact uniformity, from year to year, but are always small and nearly uniform. We presume them to be due to movements of the whole Solar System among the stars, and of the stars among each other. So far as any thing is yet known of the movements of the Solar System among the stars (93), it has been learned by the study of proper motions.

562. What is called by astronomers the **mean place** of a star for any particular time is its right ascension and declination for that time calculated after making allowance for the effect of the movement of the mean vernal equinox (545) and for the proper motion of the star. The apparent place of the star is found from its mean place by adding such small corrections as may be required. When the apparent place of a star is to be calculated for any day, its mean place for the beginning of the year in which the day occurs is first determined, and the apparent place found from this mean place. In the same way, when the right ascension and declination of any star have been observed, its mean place for the beginning of some year is found from this apparent place. All the observations of its place belonging to any particular set of

observations have thus to be compared together, in order that their accidental mistakes may be made to correct each other so far as possible (548).

563. When the movements of bodies belonging to the Solar System are observed, the observations can only be stated by the use of various terms different from any which we have yet noticed. For instance, the **nodes** of the orbit of a planet are the points where that orbit passes through the plane of the ecliptic; or, more usually, these nodes are understood to be the points on the ecliptic where it is crossed by the projection of the planet's orbit on the celestial sphere. The **ascending node** is that at which the planet is observed to cross the ecliptic from south to north; the other is the **descending node**. The **line of the nodes** is the straight line drawn in the plane of the ecliptic from one node to the other (181). Any great circle of the celestial sphere may be considered as having nodes where it crosses the ecliptic. The equinoxes, for instance, may be regarded as the nodes of the equator. The equator of the Sun, or of a planet, when regarded as projected on a celestial sphere with its centre at that of the Sun or of the planet, is usually described as having its ascending node in a certain longitude.

564. The **apsides** of an orbit are the ends of its major axis (145), or perhaps rather the points where a celestial sphere with its centre within the orbit is pierced by the line of this major axis, called also the **line of the apsides**. The **perihelion point** of the orbit of a planet about the Sun is obviously at one of the apsides, and the **aphelion point** at the other.

565. When a conjunction or opposition (327) is regarded as taking place at some particular moment, it takes place either in right ascension or in longitude, but not usually in both at once. A **conjunction of two objects in right ascension** occurs, of course, when both objects have the same right ascension. If one is then exactly in a line with the other as seen from the Earth's centre they will also be in **geocentric conjunction in longitude**; as they will, too,

if both of them are on that meridian which passes through the poles of the ecliptic as well as through those of the equator. This meridian is at once an hour circle and a circle of latitude; its plane, therefore, must be perpendicular to those both of the equator and of the ecliptic. But when a plane is perpendicular to both of two others it is always perpendicular to the line of their intersection, if they have one. Hence the plane of the meridian passing through the poles of the ecliptic is perpendicular to the line of the equinoxes; and the meridian itself, which is called the **solstitial colure**, has the equinoxes for its poles, so that it coincides with the local meridian when the equinoxes are on the horizon (536). It crosses the ecliptic half-way between the equinoxes, at the points called the solstitial points, or the **solstices**, where the ecliptic reaches its greatest declination north and south. If two objects, then, are both on the solstitial colure, they are in conjunction or opposition both in right ascension and in longitude, even if their declinations differ; while if they are on any other meridian, they are in conjunction or opposition only in right ascension, and if they are on any other circle of latitude they are in conjunction or opposition only in longitude; unless the straight line passing through them also passes through the centre of the sphere. The calculation of eclipses, transits, and occultations is usually begun by finding the time of the geocentric conjunction in right ascension of the two objects which are to occasion the particular event to be predicted. From this, its appearance and time for observers on various parts of the Earth's surface may be determined, the movement of the two objects in right ascension and declination being known.

566. As the name of solstitial colure is given to the meridian passing through the solstices, that which passes through the equinoxes is called the **equinoctial colure**.

567. A revolution from one conjunction with the Sun to the next conjunction of the same kind is called a **synodical revolution**, as we have seen (335); and the times of the synodical revolutions of the Moon and Venus, for example,

are more easily noticed than those of the sidereal revolutions. A sidereal revolution is the revolution of any object from its passage through some given plane, perpendicular to the plane of its orbit and containing one focus of that orbit, to its next passage but one through the same plane (335). Practically, however, a **sidereal revolution** is completed by the return of any object to conjunction in longitude with any star so distant that its proper motion (561) is imperceptible; the centre of the sphere being placed at one focus of the orbit of the revolving object. A sidereal revolution is actually reckoned by making a correction in the time of some other revolution so as to allow for the theoretical movement of the point from which that revolution is reckoned.

568. The **true anomaly** of a planet, at a given moment, is the angle through which its radius vector (148) has moved since the planet's last perihelion passage. Its **mean anomaly**, at a given moment, is the angle through which its radius vector would then have moved since the planet's last perihelion passage, if the radius vector moved over equal angles (instead of equal areas) in equal times, at a rate sufficient to bring it to the perihelion point at the actual time of each perihelion passage of the planet. Hence the mean anomaly is less than the true anomaly between perihelion and aphelion, greater than the true anomaly between aphelion and perihelion, and differs most from the true anomaly at those times when both anomalies are increasing at the same rate. What has been said of the Moon's movements (177) may help to make this clearly understood. The **anomalistic revolution** of any object moving in an orbit around another is its revolution from a point after passing which its distance from the body round which it moves begins to increase to the next point at which this happens. For example, the anomalistic revolution of the Earth, the time occupied by which is the anomalistic year, is the revolution of the Earth from perihelion to perihelion; the anomalistic revolution of the Moon is its movement from perigee to perigee again (335).

569. Still another kind of revolution is revolution from one

of the nodes of an orbit round to the same node; this is sometimes called **nodical revolution.**

570. The sidereal, anomalistic, and nodical revolutions of any large planet belonging to the Solar System differ little from each other. The nodical revolution is usually the easiest of the three to determine by observation, since whenever a planet appears to cross the ecliptic, it must be at one of its nodes; while the Earth, from which it is observed, does not remain in any place from which the times of the sidereal and anomalistic revolutions of the planet can be readily determined.

571. But since orbits have to be regarded as continually, though slowly, changing their planes, and their places in those planes, it is obvious that neither the nodical nor the anomalistic revolution of a planet can precisely agree with its sidereal revolution, which, as has been said, is that usually meant when the revolution of a planet is spoken of (335).

572. Although these small distinctions between different sorts of revolution may seem needless, they all have their uses in astronomical research. What has already been said of the movements of the Earth and of the Moon, will show that the different revolutions of these bodies, especially those of the Moon, perceptibly disagree in the times which they occupy. We have seen that the nodes of the Moon's orbit retrograde so rapidly as to make the complete circuit of the ecliptic once in something less than twenty years (181); hence the nodical revolution of the Moon must be shorter than its sidereal revolution; for the nodes of its orbit back round to meet it while it is going round the Earth. Again, the line of apsides of the Moon's orbit turns round with direct motion (184) once in about nine years, so that the Moon's anomalistic revolution is longer than its sidereal, though not so long as its synodical revolution; for the line from the Earth to the Sun turns round with direct motion once a year instead of once in nine years, so that the Moon's conjunction is delayed longer than its return to perigee.

573. The Earth has no nodical revolution, since the plane

of its orbit is not regarded as differing from the plane of the ecliptic. But the most important of its revolutions, so far as the ordinary reasons for dividing time into years are concerned, is its revolution from either equinox to the same equinox again. This is called the **tropical year**; it contains a little less than $365\frac{1}{4}$ days of mean time, and hence a little less than $366\frac{1}{4}$ days of sidereal time. As the year, however, must have an exact number of days in it to make it convenient for common purposes, our ordinary year, called the **civil year**, is one of 365 days of mean time. Every fourth year contains 366 days, so as to prevent the civil and tropical years from disagreeing too much as time goes on. But as the tropical year is not quite $365\frac{1}{4}$ days, the additional day usually put into the civil year once in four years is left out every hundred years. The year 1800, for instance, had 365 days, and the year 1900 will have no more. But every 400 years the day must be added to the civil year as usual. The year 2000 will have 366 days, or, according to the usual expression, will be a leap year. Further corrections, at long intervals, may be made in like manner. The reason why the civil year begins a little after the winter solstice has already been mentioned (302).

574. The seasons, and all the events connected with them, depend on the tropical year; except in the study of astronomy, then, it is the only year which is noticed. But the sidereal revolution of the Earth takes a few seconds more than its tropical revolution; for the equinoxes retrograde on the ecliptic like the nodes of the Moon's orbit, though much more slowly (167, 544). So, too, the apsides advance (169); and accordingly the anomalistic year (568) is very slightly longer than the sidereal year. There is no synodical year, since we count years only by the apparent movements of a single body, the Sun; but if we please, we may consider the time of the synodical revolution of any planet as the synodical year of the Earth with respect to that planet.

575. Any one of the moments at which the mean time clock is to agree with the sundial in the course of a year may be

chosen at pleasure, as we have seen (310). The choice is actually made in the following manner. For convenience in explaining it, it is usual to suppose an object called the mean sun, having a uniform direct motion along the equator, and passing the vernal equinox once in each tropical year. The question now to be decided is this: at what time in the tropical year is this mean sun to pass the vernal equinox? The moment chosen for this purpose is not that when the Sun actually crosses the equator from south to north, but that at which it would cross the equator, if, after the time when the Earth passes its perihelion, it moved along the ecliptic at the rate of the mean sun's movement along the equator. In other words, since the Earth passes its perihelion early in January, the moment chosen for the passage of the mean sun through the vernal equinox is the first moment after the Earth's perihelion passage at which its mean anomaly (568) is equal to the angle between the line of the apsides of its orbit and the line of the equinoxes. At this moment, the Earth's true anomaly exceeds its mean anomaly; hence the Sun is already north of the equator, in advance of the mean sun in its direct movement, and therefore behind it in its diurnal movement, so that the sundial, as we have seen (310), is slow of the mean time clock. By reckoning backward or forward from this moment, we can find the times of the four yearly conjunctions in right ascension of the mean sun with the Sun, which are obviously the times when the mean time clock should agree with the sundial.

576. It is clear that the difference of local mean time between two local meridians is the same with their difference of local sidereal time; for the mean sun passes from one meridian to the other in a fraction of twenty-four hours of mean time, equal to the fraction of twenty-four hours of sidereal time in which the vernal equinox passes from one meridian to the other. That is, when we are really speaking of the difference of longitude between the two meridians, which is an angle, it makes no difference whether this angle is measured on the dial of one clock or of another (547).

577. In reckoning mean time, the mean equinox (545) is employed; so that days of mean time are still more nearly equal to each other than sidereal days are. A perfectly uniform measure of time might be obtained (supposing the Earth's rotation to be uniform) by assigning a uniform retrograde movement to the equinox, and separating time into parts by means of the successive returns of the mean sun to this uniformly moving equinox. This plan has been proposed, and the time so measured has been called equinoctial time. It would be alike at all parts of the Earth (312). But astronomers have generally contented themselves with avoiding the use of local time, in certain calculations, by the following means. Adding together, at any given time, the heliocentric longitude of the Earth's perihelion, and the Earth's mean anomaly, we obtain an angle called the **Earth's mean longitude**. What is called the **Sun's mean longitude** differs from the Earth's by 180°. Now the astronomical year (or, as it is sometimes called, the fictitious year) is considered to begin at the moment when the Sun's mean longitude is 280°. The time called 1875.0, for instance, is the moment nearest to the beginning of the civil year 1875 when the Sun's mean longitude is 280°; and the time called 1875.5 is half a tropical year after 1875.0. The tropical year, since it is reckoned from the mean equinox, is as nearly invariable as the day of mean time; when a still less variable measure of time is wanted, it may be specially calculated for the occasion on which it is required. The actual tropical year, comprised between two passages of the Sun from the southern to the northern side of the plane of the equator, is more variable than the tropical year just described, but never greatly differs from it.

# CHAPTER XIII.

## ASTRONOMICAL INSTRUMENTS.

578. A **sundial** is made by setting up something with a straight edge so that the shadow of this edge may fall on a surface where the hours of the day may be marked. Whatever is set up for this purpose is called a **gnomon**. The edge of the gnomon by which the shadow is to be cast must be as nearly as may be parallel to the Earth's axis. If the declination of the Sun always remained the same, this would not be necessary. Suppose the plane of any great circle of the sphere to contain the edge of the gnomon by which the shadow is cast. Then suppose a point of the Sun, at some particular moment, to be also in the plane of this circle. As long as it remains there, the gnomon must cast a shadow in the plane of the same circle. But if the luminous point which occasions the shadow changes its declination without moving in right ascension, it will be carried out of the plane which passes through the edge of the gnomon and the original place of its shadow, unless this plane is that of a meridian. Hence, if the shadow did not lie at first in the plane of a meridian, its place on the dial must be changed by any movement of the Sun in declination alone. Now as the Sun has different declinations at the moments on almost any two days when it is crossing any given local meridian, the shadow of a gnomon will not daily fall along the same line when the Sun crosses a given local meridian, unless the edge of the gnomon is in the plane of that meridian. Strictly speaking, the edge of the gnomon cannot be at once in the planes of all local meridians, without forming part of the axis of the Earth. But the effect of parallax produced by removing the centre of the celestial sphere from the Earth's centre to a point on its surface (529) does not noticeably alter the

apparent place of the Sun. Hence, if the edge of the gnomon is parallel with the Earth's axis, and its shadow falls along a certain line on the dial when the Sun is crossing a given local meridian, it will fall along the same line on any other day at the time when the Sun crosses that meridian. If the edge of the gnomon is in a plane parallel to that of any local meridian, its shadow will always fall along a certain line when the Sun crosses that meridian. Thus, if the edge of the gnomon is in the vertical line, or in any other line which lies in the plane of the meridian of its own place, it will cast a shadow due north when the Sun culminates. The shadow of any thing which is upright will accordingly serve to show when it is noon by the Sun, if the line is known along which the shadow lay at noon by the clock on one of those days in the year when the clock and sundial should nearly agree. In the same way the north and south points of the horizon can be roughly determined. If the dial on which the shadow of the edge of the gnomon falls is part of the surface of a sphere having the edge of the gnomon for one of its diameters, the hours may be marked upon the dial at equal intervals; but if, as is customary, the dial is flat, the spaces between the hour-marks must differ in width.

579. Time-pieces which are to keep mean or sidereal time, and not apparent time (317), are made by giving a turning motion to wheel-work either by a weight or a spring, and keeping the motion as uniform as possible by means either of a pendulum or of a spring. If the pendulum is used, the time-piece is usually called a **clock**, whether it is driven by a weight, a spring, or by any other contrivance; but if its motion is regulated by a spring, it is called a **chronometer** if it is large, and a **watch** if it is small. It would be impossible to describe the construction of clocks and chronometers within reasonable limits in a small work like this; moreover, so far as their astronomical uses are concerned, we need only know that they are meant to run at some uniform rate, but that in practice it is impossible as yet to make them do so. Hence, in using any time-piece, we must fre-

quently determine its error, in a manner presently to be explained.

580. Various applications of electricity have been contrived for the purpose of registering time. The facts of electrical action must be learned from those treatises the object of which is to explain them; but it may be well here to describe one of the ordinary forms of the **chronograph**, an instrument by which many astronomical observations are now recorded.

581. The wheels of this kind of chronograph, like those of a clock, are put in motion by a weight, and their motion is regulated by a pendulum; but instead of turning hands upon a dial, they turn a rather short and wide tube of metal upon pivots set at each end of this tube, which is called the barrel of the chronograph. A piece of paper is wrapped round this barrel, and a pen is fixed in a frame which slowly moves along from one end of the barrel to the other. The clock-work is regulated so that the barrel may turn round with a uniform motion, once in every sidereal minute. Accordingly, if the pen is made to rest on the paper, it draws a line upon it which goes spirally round and round the barrel, the length of every turn of the spiral representing one minute of sidereal time. In the frame which carries the pen is an electro-magnet and a spring. When the magnet stops acting, the spring pulls the pen a little nearer to the end of the tube from which the motion of the frame is carrying it; and when the magnet begins to act again, it pulls the pen back to its place. The magnet is made to act by an electric current, and any clock which is to be used in the observations for which the chronograph is wanted stops this current, for an instant at a time, at regular intervals of one or two seconds. It is easy to construct the clock so that it will do this. Marks are thus made along the line drawn by the pen, which show the moments at which the clock stopped the electric current. The clock is made to omit one of its signals in every minute, so as to show when the minute began. Hence if the minute shown by the clock when it begins to

record its seconds upon the chronograph is noted, the time, according to the clock, of any second recorded on the chronograph can be ascertained after the paper is removed from the barrel. The observer is provided with means of stopping and restoring the electric current whenever he pleases. Hence he can make marks upon the chronograph of a somewhat different form from those made by the clock. When he wishes to record the time of an observation, he makes one of these marks at the moment when he notices the event the time of which is wanted. This mark will appear among the marks made by the clock, the times of which are known, as explained above: and the time when the observer's mark was made can therefore be ascertained.

582. Since electric signals may be exchanged between any two places which can be connected by telegraphic wires, the time of an astronomical observation may be recorded by a chronograph at a great distance from the place where the observation is made. The culmination of a star at San Francisco, for instance, may be recorded by a chronograph in New York; and in like manner the clocks of these two cities may be compared with each other (547). Even without using a chronograph, we may put a clock in connection with a telegraphic wire in such a manner that it will send signals along the wire at regular intervals. By this means a clock kept at an astronomical observatory is often made to send signals to different places in the country around it, so that the clocks kept at those places may be compared with it at any time. The running of these clocks is sometimes actually governed by electric apparatus, so that their pendulums all swing at the same rate as that of the pendulum in the clock by which the electric currents are interrupted.

583. When an angle can be measured by an interval of time (510, 548), a good clock or chronometer is the only instrument needed for its measurement. But most angles cannot thus be measured; and angles which cannot be measured by a clock are generally expressed only in arc, and never in time (405). They are measured on graduated circles, or

graduated arcs of circles, when the measurements need not be very precise; if great accuracy is required, the measurements are wholly made, or at least completed, by instruments called micrometers.

584. Graduated circles are usually made of metal, somewhat in the shape of ordinary wheels, so as to be light, strong, and stiff; for if they bend, their usefulness is much lessened, and if they are needlessly heavy, their own weight may bend them a little. Their graduations, or, in other words, the marks made upon them for the measurement of angles, are usually placed near their limbs; this word being applied to instruments in a sense like that in which it is applied to the disks of celestial objects (49, 183). The graduation of a circle often shows a mark for every tenth minute of arc; that is, there are 2160 marks round the edge of the circle, as nearly at equal distances from each other as they can be made. Sometimes circles are graduated to every fifth minute of arc, so that the graduation consists of 4320 marks; 360 of the marks, at equal distances from each other, are made longer than the rest, so that they may serve in reckoning degrees. One of them is taken for the point from which measurements on the circle are to begin, and numbers are engraved beside the graduation at places enough to show what number of degrees and minutes is contained in the arc between any two lines. When none of the angles to be measured are very large, a graduated arc will answer instead of a whole circle; but when great accuracy is wanted, it is best to use a whole circle, and to measure any required angle upon several different parts of it.

585. Even if the graduation is carried to every fifth minute of arc, it is not sufficient for the accurate measurement of angles. We may want to know the angle between the beginning of the graduation and some point on the limb of the circle between two of the marks. In many cases of this kind, we can obtain a sufficiently accurate measurement by using a vernier. A **vernier** is a graduated scale, the marks on which are equally distant from each other, but either

farther apart or closer together than those of the graduation with which it is meant to be used. Suppose that a circle is graduated to every tenth minute of arc, and has a vernier beside it, ten divisions of which take up as much space as eleven divisions of the circle. Then, since the arc between two neighboring divisions of the circle is 10′, the arc which eleven divisions take in is 110′. Ten divisions of the vernier take in this same arc, and the arc between any two neighboring divisions upon it is therefore 11′. The vernier is set so that one of its marks is exactly opposite the point on the circle to which we wish to measure, and the mark on it which is most nearly opposite one of the marks on the circle is then looked for. If this mark is four divisions away from the point to which we are measuring, this point is 44′ from the mark on the circle most nearly opposite a mark on the vernier, and therefore 4′ from the nearest mark to it on the graduation of the circle. With this vernier we can accordingly measure an angle upon our circle correctly within 1′. A vernier with a different graduation might enable us to measure arcs of 10″ or even less. Verniers are in common use for measurements of small distances as well as of small arcs.

586. But astronomical measurements must often be made more accurately than they can be made by means of verniers. We must then resort to **micrometers**. These are usually small frames pushed or pulled one way or the other by the turning of screws. The number of turns, or fractions of a turn, given to the screw of a micrometer, shows how far its frame has been moved. The micrometer, then, measures distances, not angles, since the movement of the frame is rectilinear, as nearly as may be. It is not adapted, therefore, to the measurement of large angles; but the angles measured by micrometers are always so small that they may be compared with each other without any error of importance by the comparison of the lengths of straight lines drawn across them from one side to the other. Moreover, the error, if there is any, may be calculated and allowed for.

587. Micrometer frames are usually set within the tubes

of telescopes, at the places where images are formed of the objects which are to be measured (483). The frames carry spider's threads or delicate lines of some kind, which are brought opposite the points to which the measurements are made. When a micrometer is used, instead of a vernier, to read a graduated circle with accuracy, it is put into a microscope, which is made like a small telescope, with an object-glass and eye-piece; but as it is used for looking at near objects, the place in the tube where the images are formed, and where the micrometer is set, is farther from the object-glass than it would be if distant objects were to be observed with the same instrument. The movable thread may be set first on a fixed mark in the microscope, and then on the nearest division of the circle as seen through the microscope; and the exact setting of the microscope with respect to the circle, which is generally the thing to be determined, may thus be measured. There are various contrivances for shortening this process in practice. Angles may be measured with micrometers to the fraction of a second of arc.

588. The name of micrometer is given to other instruments besides the frames moved by screws which have been mentioned. A **ring micrometer**, for instance, is a flat metal ring set in a telescope. The different times which are required for the passage of objects, by reason of their diurnal movement (524), across the ring at different distances from its centre, enable us to calculate the angles between the objects.

589. Telescopes and measuring apparatus are used together by astronomers in a variety of ways, only a few of which need here be noticed. The **sextant**, **quadrant**, or **reflecting circle**, all of which are different forms of what is in principle a single instrument, will first be described. It must not be confounded with the large sextants and quadrants used for measuring angles by early astronomers. The modern sextant is the most portable of all astronomical instruments, and does not need a steady foundation to rest

on; for which reason it is the only instrument with which astronomical observations can be made at sea. It is used to measure the arc between two objects on the great circle of the celestial sphere which passes through them. A small telescope is pointed at one of the objects, while a movable mirror is turned until the light which it receives from the other object is thrown upon a second mirror and thence upon the object-glass of the telescope, so that both objects are seen at once, and may be brought to apparent contact. The angle between them is determined from the angle through which the movable mirror has been turned to produce the required effect. The altitude of an object may be measured in like manner, the point of the horizon nearest to it being taken for the second object. From the altitude of the Sun observed at noon, the latitude of the place of observation may be calculated; and observations of the Sun's altitude at other times of day enable the local time to be determined when the latitude is known. Ships generally carry chronometers set to the local time of Greenwich or some other place on land; and on any occasion when the local time of a ship has been determined, it may be compared with that of the chronometers on board, with the object of finding the difference of longitude between the ship and the meridian the local time of which is kept by the chronometers (547, 576).

590. The second mirror of a sextant, by which the reflected light is thrown into the observing telescope, must be placed, of course, partly before the object-glass; but it is set so as not entirely to cut off the direct view of distant objects through the telescope which is required in using the instrument. The sextant is little used at sea except in observations of the Sun's altitude; but it is occasionally useful in observations of the Moon and stars, both at sea and on land.

591. The **transit instrument**, in its ordinary form, consists of a telescope mounted on an axis which is intended to be as nearly perpendicular as may be to the line of sight (486)

through the telescope, and also to be as nearly horizontal as possible, so that the line of sight, when the telescope is turned round, may always remain in the plane of some one vertical circle. This can never be perfectly accomplished; but the more nearly it is done, the less calculation is needed to get the required results from the observations made with the instrument. These observations consist in recording the times according to some clock or chronometer at which stars are carried by their diurnal motion across marks set in the field (483, 487) of the telescope.

592. In order to determine the error of a clock, or the longitude (547) of a terrestrial place, a transit instrument is usually placed so that its line of sight may be as nearly as possible in the plane of a local meridian; it is then said to be in the plane of the meridian. Sometimes, however, it is set in some vertical plane other than that of a local meridian, especially in the plane of some vertical circle which the star Polaris may be about crossing at the time of the observations. Observations for terrestrial latitudes are sometimes made with a transit instrument in the plane of the prime vertical (518).

593. When a carefully graduated circle is set on the axis of a transit instrument, the whole instrument takes the name of a **transit circle**, or **meridian circle**; for an instrument of this kind is always set as nearly as may be in the plane of the meridian, and used mainly for the purpose of determining the right ascensions and declinations of celestial objects. The graduated circle is usually fastened upon the same axis with the telescope, and turns round with it; in this case, the microscopes and micrometers used for measurements on the circle (587) are set on the solid piers which support the whole instrument, so that one part after another of the limb of the circle (584) is brought before them as it turns. If, then, the line of sight through the telescope is pointed towards a star as it crosses the meridian, the angles between the beginning of the graduation of the circle and the points in it lying in the lines of sight through the microscopes may be determined

by the graduation and the micrometers. If a like observation is afterwards made on another star as it crosses the meridian, the differences between the angles thus obtained and those previously recorded will show the **difference of declination** between the stars. As the line of sight through the telescope cannot be accurately pointed to any star, a micrometer of some kind in the telescope itself is used to measure the angles between the line of sight and the lines pointing to the stars.

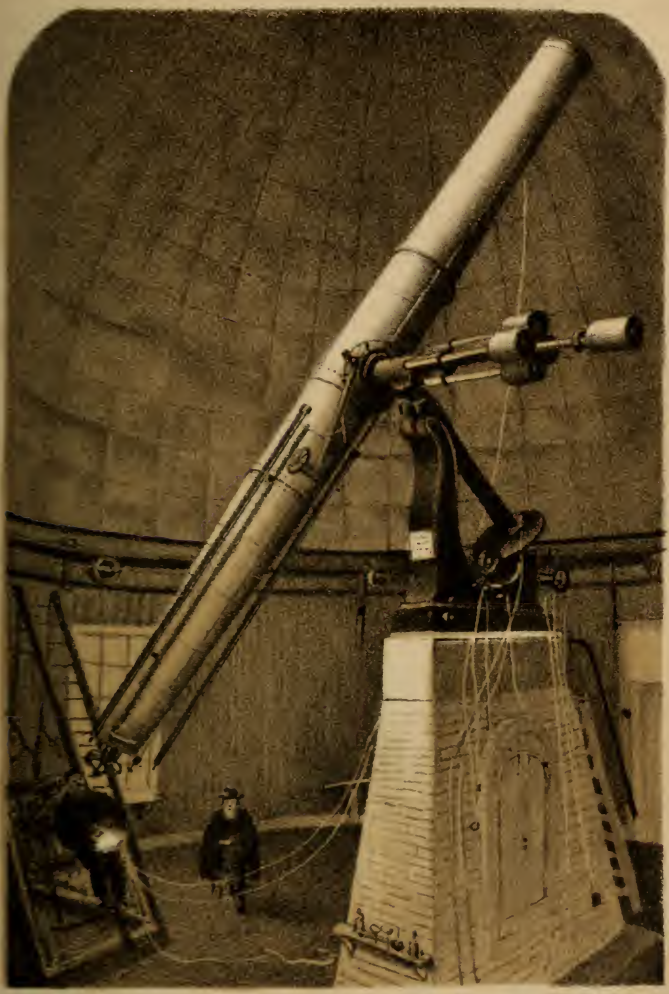
594. **Differences of right ascension** are deduced from a comparison of the recorded times of the passages of stars over the lines in the field of the telescope (548); and if **absolute right ascensions** (549) are required, the Sun also must be observed. There are various ways of determining the angles between the beginning of the graduation on the circle in any given position and the points on it through which a line parallel with the Earth's axis would pass; these angles being needed when not merely the differences of declination between different stars, but their **declinations** themselves, are required.

595. **Altitude and azimuth instruments**, in addition to the vertical graduated circles of meridian instruments, have horizontal graduated circles, and can be turned round on a vertical as well as on a horizontal axis. Instruments of this kind are seldom used for astronomical purposes, although, when made on a small scale, they are in much use among surveyors, under the name of **theodolites**. But the instruments called zenith telescopes and vertical circles, which are of use in astronomy, are in fact modifications of altitude and azimuth instruments. They are chiefly used for the determination of declinations and of terrestrial latitudes.

596. A telescope is said to be equatorially mounted, or is called an **equatorial**, when the frame which carries it may be turned upon either of two axes perpendicular to each other, one of which, called the **polar axis**, is meant to be parallel to the axis of the Earth; the other is called the **declination axis**. The chief object of this mounting is to enable the

THE GREAT TELESCOPE
Made by Alvan Clark & Sons 1873 for the U.S. Naval Observatory.

*Plate XIII.*



Tompson & Ramsay Lith. 112 Wash St Boston

This figure is copied from a photograph taken at Washington. The focal length of the telescope is about thirty feet, and its aperture twenty-six inches. It is mounted equatorially. The instrument is here represented nearly in the plane of the meridian, so that the declination axis is nearly horizontal.

observer to follow the diurnal motion of a star by simply turning the telescope on its polar axis as fast as may be necessary; this can be done by clock-work, so that a star may be kept in the field and observed for a considerable time, without the need of any movement of the telescope by the observer. Equatorials, therefore, are the only instruments suitable for observations which require much time; but they cannot be supported as steadily as meridian instruments, and are consequently unsuited to the determination of large angles. But when two objects are nearly enough in the same direction from the observer to allow them both to be seen at once in the field of an equatorial, or both to be observed within a few minutes' time and with little movement of the instrument, their differences of right ascension and declination may be accurately determined with an equatorial provided with a suitable micrometer (586, 588). Thus the place of an object which is in sight only for a short time, or of a faint object, with reference to a star seemingly near it, may be found with an equatorial, and the right ascension and declination of the star afterwards determined by a meridian circle.

597. Spectroscopes and photographic apparatus, when used in astronomical researches, are generally attached to equatorials; and equatorials are likewise employed for observations of double stars, and of parallax (559); the parallax of stars being usually determined by the micrometric comparison of their places with those of other stars too remote to have a noticeable parallax. The largest telescopes are usually mounted equatorially.

598. Instruments intended for precise observations must always be firmly mounted on foundations separate from those of the building in which they are placed, and must be protected, so far as possible, from accidental jarring, from dust, and even from sudden changes of temperature. When they are in actual use, the rooms in which they stand must be no warmer or colder, if it can be prevented, than the air outside the building; for the currents of air which would be occa-

sioned by neglect of this rule would make the images of the objects observed very unsteady. But after all possible care has been taken to make observations correct, the defects of the instruments employed in making them will render them to some extent erroneous. For example, the line of sight through a meridian circle can neither be kept long in the plane of a meridian, nor even perpendicular to the axis of the instrument. Hence arises the necessity of many calculations, by means of which these instrumental errors may be ascertained and allowed for in obtaining the results to be derived from the observations. Even when the observations have been freed from the effect of instrumental error, the remaining portions of their reduction, as the work of calculating their results is called, usually require much labor. Astronomical observations themselves are thus generally by far the smallest part of the work of astronomers. It would be useless to attempt the explanation of the methods by which the results of modern astronomy are actually reached to persons not familiar with mathematics ; but in the short account of the progress of astronomical knowledge hereafter to be given, we shall have occasion to notice the general course of observation and reasoning which has led to the conclusions accepted by modern astronomers.

# CHAPTER XIV.

## THEORETICAL ASTRONOMY.

599. WHATEVER the actual path of a moving material object may be, we always regard the object, at any particular instant, as moving in some particular direction and at some particular rate. In fact, without making this supposition, we should not know how to set about studying the movements of material objects at all. It is clearly not always a correct supposition; and we do not know that it is ever correct, for we cannot tell any thing about the actual paths of moving objects (112). But we find it answers the purpose of helping us to draw up the rules, or laws of nature, by which we can tell pretty accurately what to expect with regard to movements not yet completed (117); just as we find it practically useful to regard a moving object as first occupying one place and then another, without troubling ourselves with the puzzle how it is that this object gets from the first place to the second (393).

600. When we have occasion to consider the way in which any law of nature works in a particular case to which it applies, and at a particular instant, we often find it convenient to say that a force is acting at that instant according to that law. When the law is a law of motion, the force is a motor force; but as we shall have no need of considering any but motor forces, we may call them simply forces. The use of this word force is explained by the following statement, generally called a law of motion, but in fact rather an account of the sense to be attributed, in the study of physical science, to assertions made with respect to motor forces. *Forces act in straight lines, and are proportional to the velocities they produce.* This amounts to saying, first, that at any particular instant every material object to which any law of motion

is applicable must be regarded as moving in some particular direction at the rate required by that law; but since one law may be applied in different ways to the same object, it prevents confusion between these different applications to describe the facts for which they account as due to different forces. When we resolve (115) the motion of an object at a particular instant, and in a particular direction, into a number of motions, each in some particular direction of its own, we say, **secondly**, that the force moving the object in one of these directions, as compared with that moving it in another, is great in **proportion** to the rate of its movement in the first direction as compared with the rate of its movement in the other. Thus, if only two applications of one law, or of different laws, of motion are made at once to a particular object, and the object is consequently regarded as moving twice as fast, for example, in one direction as in another, it is said to be moved by two forces, one twice as great as the other. This use of language obviously saves many words, and therefore much labor which would otherwise be spent in considering their meaning. The astronomical use of the word force may be compared to the use of letters of the alphabet in algebra. We need not know just what these letters signify, so long as we understand that each letter never changes its signification during any particular course of reasoning in which it is employed.

601. One of the laws of motion can only be applied in one way at once to any particular object; and hence there is little need of using the word force in describing its applications. This law is that *every body continues in its state of rest or of uniform rectilinear motion, except in so far as other laws of motion may be applicable to it.* That is, if a body begins to move, there must have been a change in its circumstances, owing to which it is set in motion; and if it is once in motion, there must be some change in its circumstances either to stop it, to change the direction of its motion, or to change the rate of that motion. When a force is considered as acting under this law, it is called the **force of**

**inertia**, or simply **inertia**; and the law may be called the **law of inertia**. Headway, in common language, sometimes means inertia, as well as the movement due to inertia.

602. Another law of motion is usually expressed by saying that *action and reaction are equal and opposite.* Suppose that a ship is towed by a steam tug at the rate of four miles an hour, and that the tug could go ten miles an hour without putting on any more steam, if it did not have to tow the ship. We then resolve the motion of the tug into two; one motion forwards at the rate of ten miles an hour, and another backwards at the rate of six miles an hour. In order to explain the movements of the tug and of the ship as fully as possible, we should have to take account of a great number of laws of nature; but our present purpose makes it convenient for us, instead of stating these laws, to consider all their effects together under the name of two equal forces; one force by which the tug pulls the ship forward four miles an hour, and another force by which the ship pulls the tug backward six miles an hour. These forces are obviously opposite, and are to be considered equal. The law that action and reaction are equal and opposite requires us to suppose a reaction equal and opposite to every action whatever.

603. It may seem incorrect, in the example just given, to say that the forces by which the two vessels pull each other are equal forces; for, as we have seen, forces are proportional to the velocities they produce, and yet we have regarded the ship as pulling the tug backward half as fast again as the tug pulls the ship forward. But it has been explained that we compare forces merely by comparing the rates of the different movements of some one thing; if we compare the rate of movement of one thing with that of another, we cannot call this a comparison of forces without using the word force in two different ways in a single course of reasoning (600).

604. Every thing which we can observe differs more or less from every thing else, so that in studying it we have to make rules which apply to it alone. However, these rules

can often be drawn up by the help of others which are more general. The rule that action and reaction are equal and opposite is an instance of a general rule of this kind. By its help, in the case just given, we find an effect of certain peculiarities about the ship, which we may call the **amount of work** done in pulling that ship at the rate of four miles an hour. We feel sure, after trying this experiment, that if some other tug, built exactly like the first, can pull the same ship four miles an hour, and is then set to pulling against the first tug, neither tug will pull the other from its place. But without the rule that action and reaction are equal and opposite, we could not be sure that the action of the second tug would be equal to that of the first; since one or both of these actions might have been unequal to the reaction of the ship. Of course, in a case of this kind, we take the rule for granted, and are not obliged to think of it at all; but it should be remembered in the study of the movements of celestial objects.

605. The chief differences among the objects which we shall have to consider are differences of mass. We have seen (10) that we get our first notion of mass by noticing that bodies which differ in size, but not in hardness, color, or general appearance, differ in certain other ways in just that proportion in which they differ in size. A quart of water, for instance, is just twice as large, and also just twice as heavy as a pint of water; and just enough quicksilver to outweigh a quart of water takes up twice as much room as the quantity of quicksilver which will just outweigh a pint of water. But however the notion of mass is gained, the word is used in astronomy to mean merely those properties of any celestial object, except its shape, which make a special rule necessary for its movements and for the movements of other objects with respect to it (604). When we say that the mass of one object is three times as great as that of another we mean that a movement of the first object must be considered three times as great as a movement of the second object through the same distance; or that the two objects differ in

such a way that a movement of the first object through one foot will balance a movement of the second object through one yard, under the rule that action and reaction are equal and opposite. The amount, or quantity, of the motion of any object at any instant is found by multiplying its velocity by its mass, when this quantity is to be compared with the quantity of motion of another object. Thus, if one object has twice as much mass as another, and moves three times as fast, it has six times as much motion. By adopting general rules of this kind, and then determining one special rule for each object considered, we become able correctly to calculate many of its apparent movements in advance. The determination of the special rule is called the determination of the mass of the object. In studying the physical sciences, we do not need to consider whether the rules sometimes called laws of nature can be proved to be true in any sense except that in which we call them true because they are useful guides in foretelling what is to happen (117). There are many questions concerning them which belong to logic or to other mental sciences, but not to astronomy.

606. We seldom have occasion to lay down special rules about the movements of any particular celestial object, except the rule of its mass. But we must occasionally take the shape of an object into account as well as its mass. For example, the precessional movement of the Earth depends on its shape. In this case, however, we are really considering the masses of different parts of the Earth. There is no special rule about the Earth's movements which relates directly to its shape.

607. We now come to the **law of gravitation**, the accurate statement and explanation of which was perhaps the greatest scientific work ever done. It may be expressed as follows: *any given material object is constantly moving towards any other given material object with a quantity of motion directly proportional to the product of the masses, and inversely proportional to the square of the distance, of the two objects considered.* This law is too complex to be

readily comprehended at once; its meaning will grow somewhat clearer as we go on.

608. We must first take notice that the law of gravitation does not consist, as is sometimes fancied, in an assertion that bodies attract each other; it consists in stating *how* they attract each other, and it may be stated, as above, without mentioning attraction or any kind of force. But it often saves words and time to use such terms as attraction, force of gravity, gravity, or gravitation.

609. Secondly, we observe that as every material object has some bulk, the distances of its various points from any given point will not all be the same; while the law of gravitation requires us to take into account the distances between objects. But the objects considered in astronomy are so small compared with the distances which separate them that we may usually consider the distance between the centres (157) of any two of them to be the same as the distance between any point in one to any point in the other. Not that this can always be done; on the contrary, such movements as those to which precession and nutation are due could not be explained unless we considered the law of gravitation as applying separately to the separate parts of the Earth. We may, of course, regard any object as divided into parts as small as we please.

610. Suppose two bodies, which we will call A and Z, to be moving towards each other under the law of gravitation alone. When they are one hundred miles apart, let us suppose them to be approaching each other at the rate of ten miles a second (599). Now if we consider the mass of A equal to that of Z, we must consider A to be moving towards Z at the rate of five miles a second, and Z to be moving towards A at the same rate; or else we could not consider the quantities of motion (605) of A and Z to be the same, as we must by the law of gravitation and the law that action and reaction are equal and opposite. But if we are to consider the mass of A to be $\frac{1}{10}$ of the sum of the masses of A and Z, we must divide the joint speed of A and Z between them in a different

way, and consider A to be moving six miles a second towards Z, while Z moves four miles a second towards A; this will make their quantities of motion equal.

611. Now suppose that the mass of A is doubled, while that of Z remains as before. By the law of gravitation, the quantity of motion of each body must now be doubled; for the quantity of motion is to be directly proportional to the product of the masses, and this product is doubled if the mass of either body is doubled. Since Z has no more mass than before, the quantity of its motion can only be doubled by doubling its speed; it must therefore be moving at the rate of eight miles a second. Since the mass of A has been doubled, its quantity of motion is doubled without any increase in its speed: the joint speed of A and Z towards each other is accordingly fourteen miles a second, instead of ten miles a second as before. This joint speed, then, is $\frac{14}{10}$ as great as at first. But the sum of the masses of A and Z is also $\frac{14}{10}$ as great as it was before the mass of A was doubled; and whatever figures we use, we shall obtain a like result. The joint speed of any two objects, then, under the law of gravitation, is proportional to the sum of their masses, while the quantity of the motion of either object is proportional to the product of these masses.

612. We will next consider the meaning of the statement that under the law of gravitation the quantity of motion of either of two objects is inversely proportional to the square of their distance. Let A and Z, as we first supposed, be approaching each other at the rate of ten miles a second, under the law of gravitation alone, when they are one hundred miles apart. When they are seventy-five miles apart, their distance is $\frac{3}{4}$ as great as we first supposed it. The quantity of the motion of either A or Z is therefore the square of $\frac{4}{3}$, which is $\frac{4}{3}$ times $\frac{4}{3}$, or $\frac{16}{9}$, as great as it was when they were one hundred miles apart. As no change has been supposed to occur in their masses, the speed of either of them will be $\frac{16}{9}$ as great as it was; and their joint speed will be $\frac{160}{9}$, or $17\frac{7}{9}$, miles in a second.

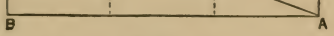
613. Accordingly, if two bodies move towards each other under the law of gravitation alone, their speed must be constantly changing. Still, we consider them to have a certain speed at every instant, as we may consider a railway train, soon after it has started from a station, to have a speed of ten miles an hour at some particular part of the track, although it may not keep that speed for the smallest fraction of an inch that can be named.

614. We have just been considering the movement of bodies under the law of gravitation alone. But every moving body is also under the law of inertia, and if two bodies are moving directly towards each other under the law of gravitation, their movement under this law is constantly added to their previous movement according to the law of inertia. But bodies are not always hurried together under the law of inertia: the effect of this law is often to keep them apart, as we shall see by inquiring how Kepler's laws (150) result from the general laws of motion.

615. Kepler's first law is only a part of one much more general, which is this: *the movement of one body with respect to another, under the laws of gravitation and inertia, must be in one of the conic sections* (414). To show this obviously requires some mathematical study of the conic sections; but without knowing their properties, we may presently get some slight notion of what the course of the required argument would be if we undertook to follow it. Kepler's second law is easier to explain. It is included in the general statement that *a body turned out of the rectilinear course, along which its inertia would carry it, by any force which at different instants is always directed to the same point, will so move that the line connecting it with that point will pass over equal spaces in intervals of time which are equal to each other.* This statement is not so complicated as it looks; still, we need a few simple geometrical facts for its proof.

616. Let us first suppose a body to be moving in two directions at once, and consider the resulting movement of any point in that body. A ship, for instance, may be moved

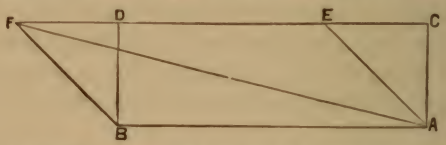
by the wind due westwards at the rate of six miles an hour, and at the same time carried due northwards by a current at the rate of two miles an hour. Then, if we consider only these facts, and no others, we shall regard the ship as driven by two forces, the directions of which are perpendicular to each other; one of these forces, which we may call the westward force, being three times as great as the other, which we may call the northward force. If we now consider the motion of any particular point in the ship during any small interval of time, we see that the point it reaches at the end of that interval is both north and west of that from which it started at the beginning of the interval, but three times as far west as north of it. Representing the points of the compass as is usual on maps, the point must accordingly move from A in the figure below to D in the same figure, during the same time in which the westward force alone would have carried it to B, and the northward force to C; the line AB being meant to be three times as long as the line AC, and these two lines being meant to be perpendicular to each other.




617. If we draw the lines AD, BD, and CD, in the figure, AD represents the line along which the moving point is carried under the joint action of the westward and northward forces, and is called one of the diagonals of the figure ABDC, which is called a **quadrilateral** because it has four sides, a **parallelogram** because it is a quadrilateral each side of which is parallel to one opposite to it, and a **rectangle** because each of its sides is perpendicular to the two to which it is not parallel. The **area** of this rectangle is the amount of surface which it takes in. This area is three times as great as it would have been if the westward force had been no greater than the northward force; as is clear when we

divide it into three equal areas by the dotted lines in the figure. The general rule which this example illustrates is that *the areas of two rectangles of equal altitude are to each other as the bases of the rectangles;* the **altitude** of a rectangle being the length of either of its sides which we please to select, and its **base** being the length of either of the sides perpendicular to that the length of which is called altitude. This rule may be proved by geometrical reasoning, which many people can make out for themselves; but it may be found in books on geometry, if it is wanted.

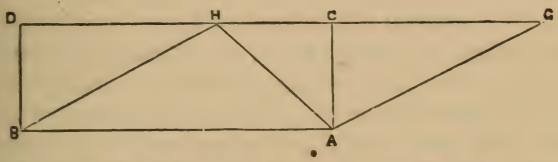
618. Let us now suppose that instead of a northward force there is a force driving the ship somewhat north-westward; so that the point the movement of which we are considering would be carried by this north-westward force along the line AE in the figure below, in the same time during which the westward




force would carry it along the line AB. If the westward and north-westward forces act together, they will jointly carry it in this same time over the line AF, one of the diagonals of the parallelogram ABFE. The distance (402) between either of the sides of this parallelogram, and the side parallel to it, may be called the **altitude** of the parallelogram. In this case, the **base** of the parallelogram is the length of either of the sides the distance between which is the altitude. If we draw lines from A and B perpendicular to AB and reaching the line of which EF is part, we shall form a rectangle ABDC, of which the length of AB may be called the base, and the length of AC the altitude. But the length of AB may also be called the base, and the length of AC the altitude, of the parallelogram ABFE. The area of the parallelogram is clearly equal to the area of the rectangle; for the rectangle might be changed into the parallelogram by taking the triangle ACE from its eastern end, and putting it on its

western end in the place of the triangle BDF. That is, the parallelogram and rectangle are equivalent (394). It is a general rule that every parallelogram which can be considered as having the same base and altitude with a rectangle is equivalent to that rectangle. This rule, too, is proved by simple geometrical reasoning.

619. Let us suppose a third case, that of a point moved at once by a westward and north-eastward force. In the following figure, suppose that the north-eastward force would move



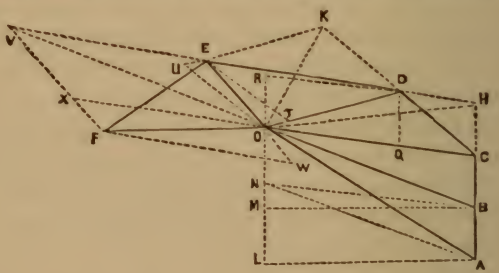

the point from A to G, while the westward force would move it from A to B. Then both together would move it in this same time from A to H. AH is one of the diagonals of the parallelogram ABHG, which is equivalent to the rectangle ABDC.

620. The lines AB and AC need not be supposed to have the same length in either of the last two figures which they had in the first figure. But if we consider them to have that length, then it is obvious that AE has been drawn longer than AC, and AG still longer than AE. In other words, our supposed north-westward force was greater than the northward force previously supposed, and our supposed north-eastward force was still greater. This shows that equivalent parallelograms may differ largely in the length of their sides.

621. We have now to notice that when a ship is moved by winds and currents, as we have supposed, the forces which move it must be constantly kept up, or it would not keep on moving. If the westward force should cease, or, in other words, if the wind should stop blowing, the resistance of the air and water would soon put an end to the westward movement of the ship. In moving westward it would push

towards the west the air and water close to its western side; according to the law that action and reaction are equal and opposite, this air and water would push the ship eastward with a force as great as that by which the ship pushed them westward; so that the westward progress of the ship, under the law of inertia, would be combined with an eastward movement, and its westward movement would be slackened. Its headway being now less than before, the resistance of the air and water would also be less, but would still continue to diminish its headway westward, until none was left.

622. But celestial objects are not known to meet with any resistance in their movements; and if they meet with any, it is very little. Accordingly, the force of inertia alone is enough to keep them moving, and if any other force is constantly aiding the force of inertia, the object moved by these forces must be always going faster and faster. In order to simplify the proof of Kepler's second law as much as possible, we shall suppose the force of inertia to be kept up steadily; but another force, which we will call the central force, to act only at particular times, and to be kept up, when it acts, for a time shorter than any time which can be named.




623. Suppose, then, that a moving point reaches A in the above figure, with a speed sufficient to carry it over the line AB in one second. If it is now moving merely according to the law of inertia, and no other, it will actually reach B in one second after it passes A, and C in one second after it passes B; BC being of equal length with AB, and being also

the continuation of AB beyond B. When the point reaches C, let us suppose a central force directed to O to come into play and cease instantaneously, as agreed upon in the last paragraph. Let this force be great enough to carry the point in one second from C to Q, provided it were the only force by which the point was moved. This supposition may also be put into the following form. When the point reaches C, let it begin to move according to some law under which it must take the direction from C to O at the rate of the distance CQ in a second of time; but let this law instantly cease to be applicable to its movement as soon as it quits C. We have now to consider the direction and rate of its movement at the instant when it passes C. By the law of inertia alone, it is moving towards H, and would reach H in a second; CH being the continuation of its former course, and equal to AB or BC. By the new law which comes into play at C, it is moving towards O at a rate which would bring it to Q in a second. If, then, we draw the parallelogram CHDQ, we see that the point, when at C, must be moving in the direction of D, and at a rate which would take it to D in a second. Now, although its movement towards Q stops as soon as it quits C, yet it already has acquired its movement towards D at the rate just named. Therefore, by the law of inertia alone, it must reach D at the end of a second after it passes C.

624. At D, we will suppose that the central force again acts, and is greater than at C; so that under this force alone, the point would reach T in one second. Completing the parallelogram DKET, and repeating our previous course of reasoning, we must place the point at E one second after it passes D. At E, let the central force act again, and be so strong that the point, under this force alone, would pass beyond O and reach W in one second; for we need not now suppose (since we are not dealing with the law of gravitation) that there is any object at O, or that our central force would bring the point no farther than O, although it always acts in the direction passing through O. Completing the

parallelogram EVFW, we find that the point must move to F in one second after passing E.

625. We will now return to the point A, and compare the spaces over which the line joining our moving point with O has been carried by its movement during each second of time. The first of these spaces is the triangle OAB; the next is the triangle OBC; the next is the triangle OCD; the next is the triangle ODE, and the next OEF. Without going farther, we will compare the areas of these triangles with each other. We shall find them all equal; in other words, the triangles are equivalent. At first sight, this is not evident, although we can see that the triangles gain in width as they lose in length. But it is not difficult to prove them equivalent, if we consider each as half a parallelogram. Beginning with OAB, we will consider it as half the parallelogram ONAB, of which OA is one diagonal, and BN the other. We need not stop to prove the triangle to be half of the parallelogram; this is obvious from the figure, and its proof may be discovered by every one for himself, or learned from works on geometry. In like manner, OBC is half the parallelogram ONBC. Let us continue the line ON, which is parallel to BC or AB, towards L, and draw AL and BM perpendicular to AB. We have now a rectangle ABML. Let us call the length AL its altitude and the length AB its base. AL is likewise the altitude of either of the parallelograms ONAB and ONBC, since it is the distance between the line OL, of which their side ON is part, and the line parallel to OL, of which their sides AB and BC are parts. The length of BC is the same as that of AB. Hence either of the parallelograms is equal in base and altitude to the rectangle, and therefore equivalent to it. Hence the two parallelograms are equivalent to each other, and their halves OAB and OBC are equivalent to each other.

626. The triangle OCH is likewise equivalent either to OAB or OBC, as is evident by the foregoing reasoning (to prove it at length, we may draw a line from C to N, so as to complete a parallelogram ONCH, of which OCH is half).

But OCH is also half of the parallelogram OCHR. Now the triangle ODC is half of this same parallelogram, as is evident if we consider both triangle and parallelogram cut in two by the line DQ. The triangle ODQ is half OQDR, and the triangle CDQ is half CHDQ; hence ODQ and CDQ taken together are half OQDR and CHDQ taken together. Consequently ODC is half OCHR, and hence is equivalent to OCH. But OCH is equivalent to OBC; therefore so is ODC. Accordingly OAB, OBC, and ODC are all equivalent.

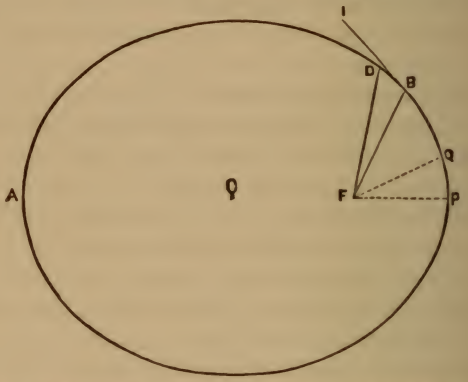
627. ODE is also equivalent to either of these triangles. For it is equivalent to the triangle ODK, which is half the parallelogram ODKU. To show that ODE is also half this parallelogram, we consider it as cut in two by the line ET; then OET is half OTEU, and DET is half DKET. Hence ODE is equivalent to ODK, which is equivalent to ODC, since DK is equal to CD, and in the same line with it; so that ODK is equivalent to ODC for the same reason which makes OBC equivalent to OHC.

628. In like manner, ODE is equivalent to OEV; and if we draw OX parallel to EV or WF, we see that OEV is half of the parallelogram OEVX and that FOW is half of the parallelogram FXOW. Hence OEV and FOW together are half of the parallelogram FWEV; but OEF and FOW together are likewise half of this parallelogram; so that OEV and OEF are equivalent. OEF is therefore equivalent to ODE.

629. There are somewhat shorter ways of proving the preceding propositions than those here adopted; and any one who knows something of geometry will be able to find them. Besides being shorter, they are more general in form; so that they may appear more convincing. But whatever method is adopted, it is now clear that the general rule in which Kepler's second law is included (615) may be readily proved when the central force acts only for a moment at a time, as we have hitherto supposed it to act, whether it amounts to nothing, as at B, or has any strength we please to suppose, as at C, D, and E. But in the orbit of any

celestial body, the central force is gravitation, which is always acting. This, however, makes less difference than may at first be thought likely.

630. We will suppose, for the present, that the Sun has no movement under the law of gravitation, but remains at rest, while other objects circulate around it. It will appear hereafter that the incorrectness of this supposition does not



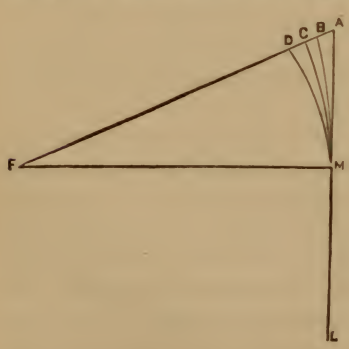

weaken the explanation which follows. The above figure represents an ellipse of considerable eccentricity, its centre being at C, and one of its foci at F, where we will suppose the Sun to be situated. The point P will accordingly mark the place at which any object revolving about the Sun in this ellipse passes its perihelion, and A the point where it passes its aphelion. Suppose this object to be at B shortly after its perihelion passage. Then its movement, by the force of inertia alone, would be directed towards I, and by the force of gravitation alone towards F. It will therefore leave B in some intermediate direction, nearly that of D. But as soon as it quits B at all, no matter how little, the force of gravitation no longer acts on it along the line BF, but along some other line. When it reaches D, for instance, the force of gravitation acts on it along the line DF. Thus, although the force of gravitation never ceases, it never acts in any one direction for any length of time which can be named. The

only way in which we can represent its action to our minds is to suppose the ellipse cut up into an immense number of little triangles, each like FBD, but as much narrower as we please. We can then suppose the moving object to be attracted to F as it comes to the boundaries between these triangles, but to cross each triangle under the force of inertia alone. Devices of this kind often have to be used in reasoning, but we must be careful not to let them confuse us when we resort to them. They form the foundation of all mathematics except simple algebra and geometry; indeed, we cannot wholly avoid them even there.

631. Considering the ellipse as thus divided into small triangles, each of them crossed by the moving object in an equal time with that in which any other is crossed by it, we have no difficulty in applying the preceding proof of Kepler's second law to the movements of the planets. For as each triangle is equivalent to any other, any number of them taken together in one part of the ellipse will be equivalent to the same number of them taken together anywhere else in it. FDB, for instance, is the space covered by a vast number of them, and is about equivalent to FPQ, which may be supposed to contain the same number of them. Since the little triangles are all equivalent, their width must differ in different parts of the ellipse, to make up for their differences in length; so that although the widest of them is narrower than any triangle which can be drawn or thought of, others must be narrower still than it is.

632. The form of the path of a point, moving according to the law of inertia and also constantly moving towards some other point which is regarded as fixed, will evidently depend on the law according to which it moves towards the fixed point, and on the speed and direction of its motion before it came under this law. Suppose, for instance, that when its motion towards the fixed point begins, it is at that point of its rectilinear course which is the nearest to the fixed point. Then it must at this instant be moving in a direction perpendicular to that of the line joining it with the

fixed point (402). Now suppose the law under which it is to move towards the fixed point to be such that the speed of this motion will not change as long as the distance between the moving and fixed points remains the same. It may seem at first that if one point moves towards another at all their distance cannot remain the same; but what has been said of the resolution of movements into others, both in this chapter and previously (114), will show that there is nothing absurd in the supposition just made. Let us also suppose that the law of the movement of the moving point towards the fixed one gives the moving point a speed, when it first comes under the law, so proportioned to the speed it previously had, that its course is changed just enough to keep it from getting farther from the fixed point, as it would do, according to our supposition, under the law of inertia alone, and would do still more quickly after its speed had been increased by the addition of a new movement in a direction perpendicular to that of the first; this must of course be taken into account in considering how much change of direction is necessary in the motion of the moving point to keep it as near the fixed point as it was when this change of direction began. Although we cannot here enter into a calculation of this kind, it is clear from the following figure that the moving point may be too slow as well as too fast in its motion towards the fixed point, always to remain at the same distance from it. If the fixed point is at F, and the moving point has reached M from L, it would go on to A under the law of inertia alone; but if it begins at M to have a movement towards F, it may cross the line FA at any point between F and A. If it turns into the course MB, it will be farther from F at B than it was at M;



if it turns into the course MC, it will be as far from F at C as it was at M; and the course MC may be such that all its points are equally far from F. In this case the moving point will continue to go round the circumference of a circle, the centre of which is at F, provided that the law under which its movement towards F takes place does not change the rate of that movement as long as the distance between F and the moving point remains unchanged. The law of gravitation is a law of this kind. Accordingly, it is theoretically possible that one point should go round and round another in an exact circle, under the laws of inertia and gravitation alone. But it is plainly very unlikely that an instance of such a movement should occur.

633. Let us next suppose the moving point to cross FA between A and C. Its course is now taking it farther and farther from F. Now if the law under which it is moving towards F is the law of gravitation, the rate of this movement is lessening; so that the moving point may perhaps always keep on increasing its distance from F. It will then be moving in a hyperbola or a parabola, most likely a hyperbola. This follows from the geometrical properties of these curves and from the exact terms of the law of gravitation; under another law we might have some other result.

634. But it does not follow that under the law of gravitation the moving point must always go on increasing its distance from F, even if it crosses FA between A and C. To understand this, we must notice that if it is at any time increasing its distance from F, its movement may be resolved into two, one directly away from F, and one in a direction perpendicular to the first. The first of these movements is checked by gravitation; and when a movement is composed of two, the directions of which are perpendicular to each other, it is lessened if either of the movements which compose it is lessened (617). The whole movement of our supposed moving point is therefore checked by gravitation; so that its headway (601) is less the farther it goes from F. Now although its movement under the law of gravitation diminishes as its

distance from F increases, yet as its movement under the law of inertia is also slackening, the comparative greatness of these changes must decide whether, after a sufficient time, the moving point does not cease to go farther from F. It may at length reach a part of its course where it is again moving in a direction perpendicular to that of the line joining it with F. In this case, its movement under the law of inertia must have been so greatly reduced that its movement under the law of gravitation afterwards begins to bring it nearer and nearer F.

635. But as it approaches F, its speed is continually increased, for a like reason to that for which its speed has previously been lessened. Its movement under the law of inertia at length overbalances its movement under the law of gravitation, in spite of the increase of this last movement as it comes nearer to F; and it again passes the point M with the same speed and in the same direction as before, repeating its movement along an ellipse, the point of which situated at M answers to the point of the orbit of a planet where the planet's perihelion passage takes place.

636. The proof of this depends on the properties of the ellipse and the strict statement of the law of gravitation. But if we admit it to be true, we see that if the moving point crosses FA between A and C, it may continue to circulate about F in an ellipse of which F is one focus, the other focus being in the direction from M to F, but beyond F. Hence, if the movement of the moving point under the law of gravitation is not great enough compared with its movement under the law of inertia to make it revolve about F in a circle, its path may be either an ellipse, a parabola, or a hyperbola, according to circumstances; but its speed in either path can never be so great at any other point in its course as at M.

637. If its movement under the law of gravitation is too great, as compared with its movement under the law of inertia, to allow its path to be circular, it must move in an ellipse; but in this case the ellipse is smaller than before, and F is

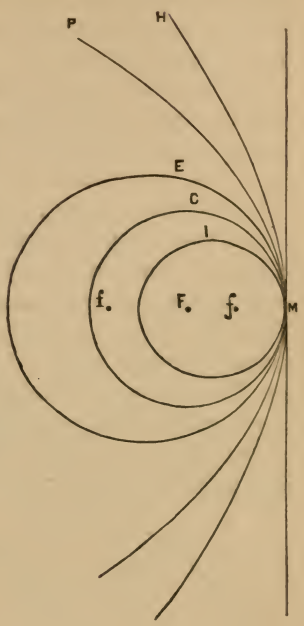
that one of its two foci which is farthest from M ; so that the speed of the moving point is less at M than anywhere else in its orbit. If its orbit is circular, its speed in that orbit must be uniform by Kepler's second law. If, when it first comes under the law of gravitation, the direction of its movement is not perpendicular to that in which it is to move under the law of gravitation alone, its path cannot be circular, but may be an ellipse, a parabola, or a hyperbola, according to circumstances. The rules just laid down will be stated more accurately at the end of the sixteenth chapter.

638. We have been supposing that the Sun remains fixed, while some other object circulates about it (630). Let us now inquire how two bodies, to both of which the law of gravitation applies, will move with respect to each other. The quantities of motion of both bodies, under the law of gravitation alone, must be equal ; and if we suppose their masses equal, their velocities will also be equal (610). Now, if they begin with no motion at all except under the law of gravitation, they will move directly towards each other ; but any other motion they may have at first in other directions will throw each into some kind of orbit about the other. Let us suppose their original motions equal, perpendicular in direction to the line joining the two bodies, opposite to each other, and just quick enough to keep the bodies from approaching each other. Then their orbits will be circular, and they will move equally fast in those orbits, so that they may be regarded as always at opposite ends of some diameter of a circle round the circumference of which they are both moving. In this case each of them may be considered as revolving, not about the other, but about a fixed point half-way between them. In other cases, which are not so simple, it is likewise found by the proper calculations that each of the two bodies moves about a point somewhere between them, and that this point is fixed, so far as the movement of the two bodies with respect to each other is concerned, although we may of course suppose it to be carried along in any movement which the two bodies may jointly have with respect to others. This fixed point is usually

called the **centre of gravity** of the two bodies. The orbits of the two bodies about their centre of gravity will be alike in shape, however much they may differ in size. If we regard either body as fixed, and examine the path of the other with respect to it, we shall find the shape of this path also to be like that of either of the bodies about their centre of gravity; while its length is as great as the joint length of the two separate paths of the bodies about that centre. The speed of either body, when regarded as moving about the other, must likewise be the same, at any particular moment, with the joint speed of the two bodies at that moment, when they are considered as moving about their centre of gravity. Each body will be nearer the centre of gravity in proportion to the greatness of its mass as compared with the mass of the other body; and its orbit will be smaller, and its speed less, in the same proportion.

639. If there were no bodies in the Solar System except the Sun and the Earth, we might consider the Sun as revolving about the Earth. But when we notice that the movements of the other planets, as seen from the Earth, can be best accounted for by supposing them all, and the Earth likewise, to revolve in ellipses about the Sun, we see that according to the law of gravitation we must suppose the Sun's mass to be so great in comparison with that of any other body in the Solar System that its movements within that system are to be regarded as very small. The law of gravitation thus makes Kepler's first law appear as a particular case occurring under a more general law; while Kepler's second law likewise appears in a more general form. The fixed point, towards which the central force acting on any planet is directed, is the centre of gravity of that planet and the Sun, when we disregard the action of the other planets, as we find in practice that we may (170). We may also regard the Sun as fixed, which will slightly increase the speed to be attributed to the planet, but will leave Kepler's second law still strictly applicable to its movements.

640. The following figure, the scale of which is smaller than that of the last figure, F being nearer to M, will show the forms of the various orbits mentioned above. MH is part of a hyperbola; MP part of a parabola; ME an ellipse with its foci at F and f; MC a circle with its centre at F; MI an ellipse with its foci at F and *f*. Ellipses with their foci as far from the ends of their major axes as those here represented can hardly be distinguished from circles.



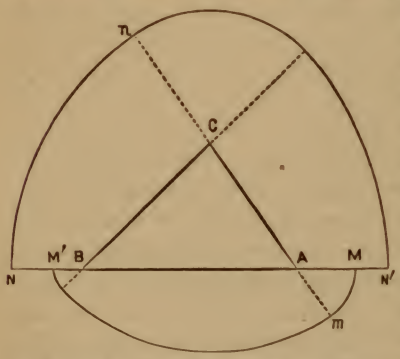

641. We have now seen what general course of reasoning must be followed to arrive at the conclusion that, under the laws of gravitation and inertia, the path of either of two bodies which we please to consider as moving about the other will be one of the conic sections (615). The convenience of regarding one or the other body, or both of them at once, as moving, depends on the comparison of their masses (638). We have also seen why it is convenient, in forming a general view of the movements which occur among the bodies of the Solar System, to consider the Sun as fixed, and the planets as moving only around the Sun and not at all around each other. However, when accuracy is necessary, we take into account, in considering the movement of any one planet, the slight changes in its orbit occasioned by its place with respect to other planets. These changes are called perturbations (170).

642. Satellites are so near the planets to which they are considered as belonging, that it is most convenient to regard

them as moving around their planets, and subject only to perturbations by the Sun; although the attractive force of the Sun may actually be greater on a satellite than is that of the planet to which it belongs.

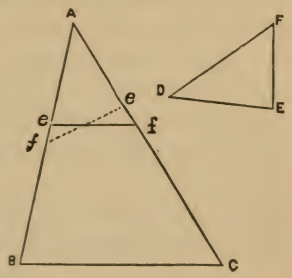
643. Comets, as we have seen (232), are usually considered to move in parabolas; but this means that we usually see so small a portion of a comet's orbit that the shape of the whole orbit cannot be exactly determined.

644. Kepler's third law can be proved without much difficulty if we suppose it applied only to orbits which are exactly circular. But even for this partial proof, we need a few geometrical propositions, in addition to those already explained. First, *the angles of every plane triangle, taken together, amount to* 180° (419). The most obvious proof of this is obtained by considering how much movement of rotation is enough to bring a straight line into the direction of each of the sides of a plane triangle in turn. In the following figure, for instance, let part of the line MN coincide with the side AB of the triangle ABC; then let MN rotate on an axis passing through A and perpendicular to the plane of the triangle, until part of it comes into coincidence with AC; M will then be at *m* and N at *n*. By a similar rotation on an axis passing through C, part of MN may next be brought from its new position to coincidence with BC; and a final rotation on an axis passing through B will bring part of MN to a new coincidence with AB, M being now at M′ and N at N′, so that the last direction of MN is contrary to its first direction. It has therefore been turned half round; or, in other words, it has been turned through 180°. But in its first rotation it was turned through the angle BAC, in its



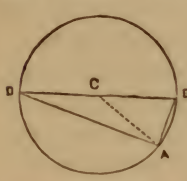
second rotation through the angle ACB, and in its third rotation through the angle ABC ; hence these three angles amount to 180°. This proof, like all other proofs of the same proposition, depends on taking certain facts about straight lines for granted. These facts are not disputed ; but what is the best way of stating them has never yet been settled. One way is that which has been adopted above, in the chapter on geometrical terms.

645. Next, if each angle of either of two plane triangles is equal to one of the angles of the other triangle, the comparative length of any two sides of either triangle is the same as the comparative length of the two sides of the other triangle, the angle between which is equal to that between the two sides first chosen. This may be stated more briefly as follows : *if the corresponding angles of two plane triangles are equal, the sides including those angles are proportional.* In the next figure, the angle at D of the small triangle is meant to be equal to the angle at A of the large triangle ; the angle at E equal to the angle at B, and the angle at F equal to the angle at C. Hence, according to the proposition just stated, DE must be the same fraction of DF that AB is of AC. If AB is just seven-eighths of AC, then DE is just seven-eighths of DF. If a piece of paper is cut into the shape and size of DEF, and laid on the upper part of ABC, so that D may fit A, it will depend on which side of the paper is uppermost whether E comes to e and F to f or E to *e* and F to *f*. Let us take the first of these arrangements ; then as the angle E is equal to the angle B, the line ef will be parallel to BC. If we measure off the line AB into lengths each equal to Ae, and AC into lengths each equal to Af, it is plain that there will be the same number of lengths and the same fraction of a length in AB and in AC. The full proof of this may be

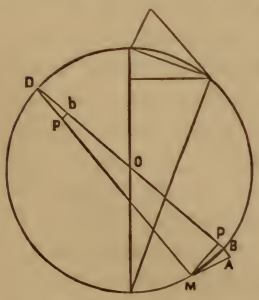


found in works on geometry, where it is also shown that it follows, as almost any one can see for himself, that Ae is contained in Af as often as AB in AC.

646. We shall also require the proposition that *two lines, meeting on the circumference of a circle, and passing through the ends of one of its diameters, must be perpendicular to each other.* In the next figure, let the two lines BA and AD meet at A, and let BD be a diameter of a circle having A in its circumference. The centre of this circle will be at C, halfway from B to D. If we draw the line CA, we shall have two triangles ACB, ACD, each of which has two of its sides radii of the circle, and therefore equal to each other. Hence the angles opposite these sides are likewise equal to each other; that is, the angle BAC is equal to ABC, and the angle CAD equal to CDA. The proof of this is easy, and need not be given here. Hence the sum of BAC and CAD, or the angle BAD, is equal to the sum of ABC and CDA. But all these four angles are together equal to 180°, since they make up the three angles of the triangle ABD. Hence, BAD is an angle of 90°; in other words, AB is perpendicular to AD.




647. We must next apply the results just obtained to the study of movement in circular orbits. Let the arc between M and B in the annexed figure be part of the circular orbit of a moving point about another point fixed at O. If the moving point went on from M under the law of inertia alone, it would go towards A instead of B. Suppose the distance from M to A to be equal to the length of the arc between M and B; then the distance between A and B shows nearly, but not exactly, how far the moving point has travelled under the law of gravitation alone in the time which it



occupies in passing from M to B. If we draw a line from M perpendicular to the line from O to B, and meeting it at P, the distance from B to P is nearly the same as that from B to A. But, as is shown by the additional lines of the figure, if the arc between M and B were made longer, there would be more difference between the distance from A to B and that from B to P; and also more difference between either of these distances and the distance travelled by the moving point under the law of gravitation alone in the time during which it moved over the arc. In fact, these differences grow disproportionately great as we take larger and larger arcs into account; while if we take smaller and smaller arcs into account, the differences dwindle away much faster than the arcs: so that when the arc is smaller than any arc which can be named, the differences are a smaller fraction of this small arc than any fraction which can be named. To understand this thoroughly, some mathematical knowledge is wanted; we must here take the fact on trust. Any error, then, which we may make in our calculations, by supposing the distance from B to P to be the distance through which the moving point passes under the law of gravitation alone while it moves from M to B, may be remedied by supposing the arc between M and B to be smaller than any arc which can be named. In like manner any error may be corrected which may result from our considering the distance between M and B equal to the length of the arc between those points.

648. The triangle DBM has a right angle at M (646); and the triangle MBP has a right angle at P, since P is the point where a line drawn from M perpendicular to the line from B to D crosses that line. Both triangles have the same angle at B. Now as the triangle MBP has two of its angles equal to two of those in the triangle DBM, and as the angles of each triangle, taken together, amount to 180° (644), the third angle of the triangle MBP must be equal to the third angle of the triangle DBM; so that the triangle MBP might be turned over and placed with its point P at p and its point B at b, its point M coinciding with D. In the triangle MBP,

the distance from B to P is a certain fraction of the distance from M to B; and in the triangle DBM, the distance from M to B is a certain fraction of the distance from D to B. These two fractions are equal (645).

649. We must now state these facts in algebraic language, or our reasoning would not be clear, owing to the number of words it would require. Readers unacquainted with algebra need only be told that each letter used as an algebraic symbol stands for some number which need not be precisely stated, because its value remains the same throughout the whole of the course of reasoning in which it is employed. Letters written together denote the product of the numbers for which they stand, and this product is to be multiplied by any number placed before the letters; thus, $2ab$ stands for 24 if $a$ denotes 4 and $b$ 3, or for 60 if $a$ denotes 5 and $b$ 6. It makes no difference in what order we write the factors of a product; and instead of repeating a letter or a number, we may denote the number of times it is used as a factor by a number called an exponent; thus we may write $2^2$ instead of 4, which is the product of 2 by itself; and instead of $abcabd$ we may write $a^2b^2cd$. $3cd$ multiplied by $3ac$, and this product multiplied by $3bc$, may be expressed by $3^3abc^3d$, or $27abc^3d$. In an algebraic fraction, the denominator is considered as a divisor, and the numerator as a dividend; a factor common to both numerator and denominator may be struck out; the fraction is multiplied by multiplying its numerator or by dividing its denominator, and divided by multiplying its denominator or by dividing its numerator; all these rules being exactly the same as those of arithmetical fractions. The sign = shows that the two expressions between which it stands denote numbers which are equal to each other.

650. Let $t$ stand for the number of seconds required for one complete revolution of the point which we supposed to move in the circumference of the circle in our last figure (647); and let $r$ denote the number of feet in the radius of the circle. Then the number of feet in the diameter of the circle will be denoted by $2r$, and the number of feet in its

circumference by about $\frac{8}{113}\frac{5}{5}$ of $2r$, or more precisely by $2\pi r$ (411). Accordingly, since the point moves at a uniform rate (637), the number of feet which it traverses in one second will be the number of times that $2\pi r$ contains $t$; and we may write this in the form of the fraction $\frac{2\pi r}{t}$. Now if we denote by $i$ the number of seconds in which the moving point traverses the distance MB (which we have agreed to consider equal to the number of seconds in which it traverses the arc MB), we may denote the number of feet in the arc MB by $\frac{2\pi ri}{t}$, which may denote a very small fraction of one foot, if $i$ denotes a sufficiently small fraction of one second, however large the number $\frac{2\pi r}{t}$ may be.

651. Let $g$ stand for the number of feet traversed by the moving point, in the time $i$, under the law of gravitation alone; we have agreed to consider this equal to the number of feet in the distance BP. It follows from the equality of fractions obtained above (648) that if we divide $g$ by $\frac{2\pi ri}{t}$, and $\frac{2\pi ri}{t}$ by $2r$, the quotients will be equal. The second of these quotients is to be denoted, in accordance with our rules, by $\frac{\pi i}{t}$. If we multiply each quotient by $\frac{2\pi ri}{t}$, the products will be equal, by the ordinary rules of arithmetic. The result of first dividing and then multiplying $g$ by $\frac{2\pi ri}{t}$ is to leave its value unchanged; accordingly $g$ is equal to the product of $\frac{\pi i}{t}$ by $\frac{2\pi ri}{t}$, which is $\frac{2\pi^2 ri^2}{t^2}$.

652. Let us now suppose a second point moving in a circle larger than that the radius of which contains the number of feet denoted by $r$, but moving, like the first point, under the laws of gravitation and inertia, round a point fixed at the centre of the larger circle. If we denote by T the number of seconds in which this point goes once round the circumference of its circle, and by R the number of feet in the radius of that circle, we may show, as before, that the number of feet traversed in the time $i$ by the second moving point, under the law of gravitation alone, is to be denoted by $\frac{2\pi^2 Ri^2}{T^2}$.

653. Let us also suppose the masses of the bodies at the

centres of the two circles to be equal to each other, and the masses of the bodies to which the moving points belong to be equal to each other. The movements of the moving points, under the law of gravitation alone, must then be inversely proportional to the squares of the numbers denoted by $r$ and R. That is (612), if we divide $\frac{2\pi^2 r i^2}{t^2}$ by $\frac{2\pi^2 R i^2}{T^2}$, the quotient will be equal to that of $R^2$ divided by $r^2$. The arithmetical rule for the division of one fraction by another is to multiply the numerator of the dividend by the denominator of the divisor for the numerator of the quotient, and the denominator of the dividend by the numerator of the divisor for the denominator of the quotient; a rule which plainly follows from the general rules for fractions (649). Our result, accordingly, will be $\frac{2\pi^2 r i^2 T^2}{2\pi^2 R i^2 t^2} = \frac{R^2}{r^2}$. Striking out the common factors $2\pi^2 i^2$ in the numerator and denominator of the first fraction, we have $\frac{rT^2}{Rt^2} = \frac{R^2}{r^2}$. Multiplying each of these equal numbers by R and dividing each by $r$, we have $\frac{T^2}{t^2} = \frac{R^3}{r^3}$, which is Kepler's third law (150) expressed algebraically, on the assumptions that the orbits considered are circular, and that the bodies moving in them have so little mass compared with the central body that their masses may be considered equal, and the central body regarded as at rest. The assumption that the orbits are circular is not necessary; it has here been made on account of the difficulty of the geometrical propositions required to prove Kepler's third law for elliptical, parabolic, and hyperbolic orbits. The second assumption may properly be made when we are studying the movements of the planets, unless we require our conclusions to be very accurate; for the mass of the Sun is more than a thousand times greater than that of Jupiter, the largest of the planets.

654. We can now understand how the masses of any celestial objects, or the special rules of motion relating to them (605), are to be ascertained. The speed with which two material objects approach each other, under the law of gravitation, depends, as we have seen (611), on the sum of their masses. Let us go back to the expressions $\frac{2\pi^2 r i^2}{t^2}$ and $\frac{2\pi^2 R i^2}{T^2}$, which

denote the numbers of feet which our two moving points traverse in the time $i$, under the law of gravitation alone ; and let us suppose the sum of the masses of the body moving in the large circle and the body fixed at the centre of that circle to be contained in the sum of the masses of the other pair of bodies a certain number of times, which we will denote by $n$. The movement of this other pair of bodies towards each other, or of either body towards the other, regarded as at rest (638), will then be $n$ times quicker, with respect to the movement towards each other of the bodies of the first pair, than we previously supposed it to be. Therefore, if we now divide $\frac{2\pi^2 r i^2}{t^2}$ by $\frac{2\pi^2 R i^2}{T^2}$, our quotient will be $n$ times as great, with respect to the quotient $\frac{R^2}{r^2}$, as it was before. We have, then, $\frac{rT^2}{Rt^2} = \frac{nR^2}{r^2}$, or $\frac{T^2}{t^2} = \frac{nR^3}{r^3}$ ; and multiplying each of these equal quantities by $r^3$ and dividing each by $R^3$, we have $\frac{T^2 r^3}{t^2 R^3} = n$.

655. Hence, if we know the distance between two objects, the time in which either revolves about the other (638), and the distance and time answering to these in the case of another pair of objects, the movement of each pair not being subject to any important perturbations (641), we can find how many times the sum of the masses of one pair is contained in that of the other. Indeed, it is only the difficulty of the mathematical operations required when the orbits to be considered are not circular and are subject to very large perturbations, that keeps us from determining the comparative masses of any three bodies circulating about each other and not subject to other perturbations than those which each of them occasions in the movements of the other two. For three bodies may be considered as arranged in either of three ways so as to form a pair of bodies with one left over ; from the letters $a$, $b$, $c$, for instance, we may form the pairs $ab$, $bc$, $ac$. Practically, however, we have to confine ourselves to such cases as those which are actually observed in the Solar System. That is, the comparative masses of three bodies can only be ascertained when they can be so arranged in pairs that the movements of the bodies of each pair with respect to

each other are altered only a little by the place of the third body.

656. We shall naturally begin our inquiry into the masses of celestial objects by comparing the mass of the Earth with that of the Sun. The most direct way of making this comparison is to take some small piece of the Earth itself, such as a leaden weight, for the third body which will be required, as we have seen, to carry out our purpose. This weight will have no mass which is noticeable in comparison with the mass of the Earth; and in our experiments with it, it will be so close to the Earth that its movements with respect to other bodies will be practically equal to those of the Earth itself. Hence we shall neither have to consider that the Earth moves, nor that the weight moves except with respect to the Earth.

657. We will first suppose that we can make the weight circulate about the Earth, near its surface, under the laws of gravitation and inertia alone. We are then to observe the distances from the Earth's centre to the weight in its various places, and also to observe how much time the weight requires to go once round the Earth. We know the time (called the sidereal year, 567, 574) in which the Sun apparently revolves about the Earth; and we also know about how far the Sun is from the Earth. Thus we obtain the number of times that the sum of the masses of the Earth and the weight, which is practically the mass of the Earth, is contained in the sum of the masses of the Earth and the Sun. To make our calculation a little more accurate, we ought first to determine the mass of the Moon; for the Moon may be considered as a part of the Earth, so far as the Earth's revolution about the Sun is concerned. Since the Moon is so much nearer the Earth than the Sun is, the movements of both Earth and Moon with respect to the Sun are very much alike; hence we may use the process just described in finding, first, how the mass of the Earth compares with the sum of the masses of the Earth and Moon; and next, comparing this sum with the sum of the masses of the Earth, Moon, and Sun; the Earth and Moon being considered as one body.

658. We may compare the sum of the masses of the Earth and Moon with the sum of the masses of the Earth, Moon, and Sun, by taking the Earth and Moon for our first pair of bodies, without using the weight which we have supposed to circulate around the Earth; in this way, however, we should not be able to compare the mass of the Earth separately with that of the Sun. The mass of the Moon, in practice, is best determined by means of the facts of precession and nutation. The distance of the Sun, and hence the length of the Earth's orbit, is not yet known accurately enough to allow us to determine the masses of celestial objects with great precision. Hence it is practically needless for us to distinguish between the mass of the Earth and the sum of the masses of the Earth and Moon, as we have done above.

659. Although we cannot make any thing revolve about the Earth like a satellite, we can learn how fast it would revolve at any given distance from the Earth, by noticing the rate at which it falls, when it is lifted from the ground and let go. It is not easy to observe this rate directly, but it can be ascertained in various ways; in particular, it may be calculated from the rate at which a pendulum swings. Our knowledge of the comparative masses of the Sun and the Earth has been gained, to a considerable extent, by counting the number of times that a pendulum of known length will swing during a given interval. The part of the Earth at which the experiment is tried makes a difference in the result, which has to be allowed for by calculation (160). From these observations and calculations we obtain our special rule of movement in the case of the Sun (605). This rule, as we have seen (47), is, that any movement of the Sun must be considered some 320,000 times as great as a movement made by the Earth through the same distance; just as the movement of 320,000 quarts of water through one foot is to be considered 320,000 times as great a movement as that of 1 quart of water through one foot.

660. The masses of the various planets of the Solar System are usually expressed in fractions of the mass of the Sun. If

a planet has satellites, the joint mass of the planet and its satellites may be compared with the mass of the Sun in the manner just described. If it has no satellites, its mass must be ascertained exclusively by the small perturbations (641) it produces in the orbits of other planets. Both these methods are available in the case of the planets Jupiter, Saturn, Uranus, and Neptune. The masses of planets which are too small to occasion noticeable perturbations in the orbits of other planets, cannot be accurately determined. Something has been learned of the masses of Jupiter's satellites by the effects produced by each satellite on the movement of the others. We also know that the sum of the masses of the asteroids cannot be great in comparison with the Earth's mass; but the mass of any individual asteroid is unknown.

661. The masses of the two stars forming a binary star can be determined from the rates at which they move; but these rates cannot be known unless we know the distance between the two stars at given times; to know this distance, again, we must know the distances of the two stars from the Earth; but these distances are seldom known at all, and in no case known accurately. Hence we have only slight knowledge of the masses of the stars; but it is likely that these masses often exceed that of the Sun (80).

662. In order to compare the mass of a celestial body with that of a cubic foot of lead, or of a quart of quicksilver, we must first know what fraction this is of the Earth's mass. This can be learned in various ways; and the results obtained by different methods agree together better than would have been expected. We find that the Earth's mass is equal to that of a body of the size of the Earth, having in all its parts a density about five and a half times as great as that of water. According to this, the number of tons of material in the Earth would be roughly expressed by the figure 6 followed by twenty-one ciphers.

663. The most direct method of comparing the Earth's mass with that of a leaden ball is to balance a small weight very delicately and measure carefully how far it will change

place when the leaden ball is shifted from one side of it to the other. This is called the Cavendish experiment. Other methods are the observation of the rates at which a pendulum will swing in a deep mine and on the surface of the Earth, or on the top of a mountain and at the sea level; also the alteration of the vertical line, as determined by a suspended weight, on opposite sides of a mountain. But in the use of these methods the density and extent of the layers of rock near the place where the experiments are tried must be known; and this cannot be completely discovered.

664. A statement of the Earth's mass in tons, like that just given, has not a perfectly distinct meaning. A ton is the name of a certain weight; now the same body has somewhat different weights in different parts of the Earth, although its mass always remains the same. So long as we continue to weigh one body against another, their comparative weights will be the same wherever we may take them. But if we weigh a lump of lead, at different terrestrial places, with a spring balance of sufficient delicacy, we shall find that its weight is less, or, in other words, that it stretches the spring less, the nearer we bring it to the equator. This effect depends, as we have seen (160), on the varying distance of the body which is weighed from the centre of the Earth, and on the increasing rapidity of the Earth's rotation as we approach the equator.

665. Hence two bodies of equal mass situated on different planets must have different weights. At the surface of the Sun, the weight of any object would be about twenty-eight times what it is at the surface of the Earth. In a deep mine, the weight of every thing is slightly greater than its weight when it is taken to the mouth of the shaft; hence a pendulum swings quicker the deeper into the Earth it is taken, so that it may be used, as just stated, for determining the mass of the Earth (663).

666. The direction of the vertical line varies like the weight of objects; for the determination of this line at any terrestrial place obviously depends upon the form of the

Earth and the density of its various parts. If a large mountain, for instance, is north of the place of observation, what appears to be a vertical line will point south of the zenith and north of the nadir which would have been found if the land to the northward had been low. To understand this, we need only remember that the reason why a weight, when let fall, drops nearly towards the centre of the Earth, is that this must be the result of the various movements which it has towards all parts of the Earth at once, under the law of gravitation. But as it moves most rapidly towards the nearest parts of the Earth, it may be slightly turned from its course by a neighboring mountain, or by the greater density of the ground on one side than on another of the place where it is let fall. If the vertical lines found by observation in different parts of the Earth all crossed each other at any one point, we might call this point the Earth's centre of gravity. But in fact they do not meet in any one point, although none of them pass very far from the middle of the Earth's axis. The general form of the Earth has usually much more effect on the determination of vertical lines than is produced by unequally dense or uneven ground. As the polar diameter of the Earth is the shortest (159), a weight let fall at almost any place north of the equator will come to the ground a little to the south of the place where it would have fallen if the Earth had been exactly spherical. Hence, as a general rule, the zenith (515) determined by observation, anywhere north of the equator, will be a little north of the point where a line from the Earth's centre through the place of observation would pierce the celestial sphere. In the southern hemisphere the observed zenith will be south, instead of north, of the corresponding point of the celestial sphere. Now as every terrestrial latitude is determined from the observed zenith of the place where the observations are made (542), this **geographical latitude**, as it is called is a little greater than **geocentric latitude**, or the angle between two lines from the Earth's centre in the plane of the local meridian, one drawn to the equator and the other to the

place of observation. Geocentric latitude and geographical latitude agree, however, at the poles and at any place on the equator.

667. Suppose that we know the length in miles of one quarter of a terrestrial meridian (517), measured along the sea level (256) of the various parts of the Earth from one of the poles to the equator. If two points on this quarter meridian, and near the equator, differ in geocentric latitude by 1°, the number of miles in the distance between them must be a little greater than the number of miles between two places on the same quarter meridian, and near the pole, which likewise differ by 1° in geocentric latitude; because, near the pole, the line on which the measurements are made lies comparatively near the centre of the Earth, and therefore crosses the lines which form the sides of the angle of latitude before they have spread apart as far as they have at the distance of the equator from the Earth's centre. But since the geographical latitude of a place is a greater angle than its geocentric latitude, except on the equator and at the poles, it follows that as a traveller goes from the equator towards either of the poles, his geographical latitude must at first be increasing faster than his geocentric latitude, but after a time must increase more slowly than his geocentric latitude, so that the two kinds of latitude may each come to 90° at the same time, when the traveller reaches the pole. Hence if two places near the equator differ as much in geocentric latitude as two places near the pole, they will differ more than the two places near the pole in geographical latitude. This may result, and in fact it does result, in making the number of miles between two places on the same meridian, and near one of the poles, greater than the number of miles between two places on the same meridian, and near the equator, when the difference of geographical latitude between the two places of each pair is the same.

668. The figure of the Earth may be determined, therefore, by determining the latitudes of a number of places at different distances north or south of the equator, and then survey-

ing the distances in miles between some of these places and others near them, which need not be exactly on the same meridian, because their differences of longitude can be allowed for in the calculations. The latitudes of the places are determined by astronomical observations (542); the distances from each other of the places to be connected by any particular survey are found by first measuring a line some few miles in length, called the base of the survey, and measuring the visual angles between various terrestrial objects seen from the ends of this base. This enables the distances of the objects observed from the ends of the base to be calculated; and thus the length of many lines much longer than the base itself becomes known without the need of actual measurement. These long lines may now be used to determine others; and a network of imaginary lines is thus spread by degrees over the face of the country surveyed, until the distances in miles between any two places in it can be found with all the accuracy which may be required. All this work is of the same sort as the determination of the distances of celestial objects by means of their parallax. It is useful for many purposes besides that of the determination of the shape and size of the Earth. It enables us, for instance, to make accurate maps of the coast or of the inland parts of any country which has thus been surveyed.

669. The Earth's precessional movement, like the variations of the weight of terrestrial objects and those of the length of different degrees of latitude, is due to its shape. One conclusion to be drawn from the law of gravitation is that a perfect sphere, of uniform density throughout, will move as if its whole mass were compressed into a mere atom placed at its centre. A body of this kind would have no precessional movement. But when the Moon is north of the plane of the equator, the equatorial parts of the Earth on the side next the Moon are so much nearer the Moon than the parts answering to them on the opposite side of the Earth that they get a slight northward movement with respect to those opposite parts; this tilts the Earth slightly,

so that if its movement of rotation did not constantly change the side of it which faces the Moon, the angle between the plane of its equator and that of the Moon's orbit would begin to diminish. According to the law of inertia, however, this cannot actually happen; and instead of rocking on an axis perpendicular to the line joining it with the Moon, the Earth gets the peculiar twisting movement to which precession is due. If the Moon is in the plane of the Earth's equator, it ceases, for the moment, to change that plane; and at other times, whether it is north or south of the equator, its action is continually varying; but the inertia of the whole Earth makes the precessional movement nearly uniform. The Sun, too, has its share in occasioning precession; but although the Sun's mass is vastly greater than the Moon's, it is so far from the Earth that the difference of its distances from the nearer and farther sides of the Earth is trifling compared with either of these distances. Hence its effect is less than that of the Moon. Even the planets have something to do with precession, but only because they draw the Earth out of its orbit, and so change the plane of the ecliptic; the effect of this on precession is called **planetary precession**, while that of the change in the plane of the equator due to the Moon and Sun is called in part **luni-solar precession**, and in part **nutation**.

670. The Moon has a precessional movement (181), from which it has been inferred that it is not a perfect sphere (187). The other bodies of the Solar System may have similar movements; but the directions of their axes are not very accurately known, and hence we cannot observe small changes in these directions. The satellites of Jupiter and Saturn are always nearly in the planes of the equators of those planets, so that it is not likely that Jupiter and Saturn have much precessional movement, although they seem to be still less nearly spherical than the Earth.

671. If a quantity of any kind of liquid is placed so far from other bodies that its separate parts may be considered as being all equally distant from any one of these bodies, the

movements of its various parts with respect to each other will bring it, under the law of gravitation alone, into the shape of a sphere. But if a liquid sphere is near enough to some other material object to make any noticeable difference in the distances of its separate parts from that object, it can no longer keep its spherical shape. For this difference in distance must make a difference in movement under the law of gravitation. If we suppose several objects all in a line with each other, one of which, Z, is farther from the others, A, B, C, etc., than they are from each other, it is plain that the movement towards each other of A, B, and C, must be less than it would be if there were no Z; since the movement of each of them towards Z is small in proportion to the square of its distance from Z. If the mass of Z is great compared with the masses of the other bodies, they may be actually drawn apart from each other by the difference of speed in their movements toward Z; on the other hand, their movements towards each other may be sufficient to prevent them from being actually drawn apart. In either case, however, their places with respect to Z make a difference in their movements, which is usually expressed by saying that their attraction for each other is lessened by Z.

672. The movements of the separate parts of a liquid sphere, undisturbed by other bodies, are so balanced against each other by the law of gravitation that each part remains at rest. But if this equilibrium, as it is called, is disturbed by another body, the parts of the sphere must move with respect to each other until they have again come to equilibrium in some new arrangement. This will change the sphere, in most cases, to a spheroid with one axis longer than any other; and the long axis will point towards the disturbing body. We may get a general notion of this process by considering the weight, though not the mass, of the parts of the sphere in a line with each other and with the disturbing body to be lessened. Under these circumstances the parts on each side will crowd in upon them, and the sphere will be pushed out of shape. When this change has

gone far enough for the increased bulk of the spheroid, along the line pointing to the disturbing body, to make up for its diminished weight along this line, the equilibrium of its parts will be restored.

673. This consideration enables us to account for the fact that the Moon raises the tide on the side of the Earth from which it is farthest as well as on that which faces it. The solid parts of the Earth are not free to change their shape, but the ocean may have some movement with respect to the Moon like that of the outer parts of a liquid spheroid. The easiest way to understand the rise of the tide on opposite sides of the Earth at the same time is to regard the water as lightened more or less according to its distance from the line passing through the centres of the Moon and Earth, the water along this line being lightened most. But where it is lightest it must also be deepest; that is, its surface must reach farther from the centre of the Earth than that of the heavier water on both sides of it, in order to balance the pressure of this heavy water. In like manner, the surface of the ocean near the equator always stands farther from the Earth's centre than the surface of the ocean near the poles (162). The Moon has little effect in lightening the ocean compared with the effect of the Earth's shape and rotation; for the level of the water at the equator differs from that of the polar oceans by about twenty-six miles, while the tides around islands in the open ocean only rise two or three feet. In narrow bays and in rivers, the various currents of water which are started by the tide sometimes make the sea rise much more than it does in the open ocean (278).

674. As the Earth's rotation turns one part of it after another towards the Moon, the places where the tide is highest at the time are steadily changed. Hence there are ordinarily two high tides every day; but the day, if measured by the Moon, is longer than a day of mean time (340). The movements of the ocean which occasion the tides must obviously be altered by the inertia due to the Earth's rotation; so that even if the Earth were wholly liquid, or wholly covered with

water, it would not follow that the two places where the water, at any given time, was deepest, would be those nearest the Moon and farthest from it. Moreover, the distribution of land and water on the Earth's surface makes the actual tides of any place dependent on various tidal waves and currents; so that the time of high tide is not often very near the time of the Moon's culmination, but usually comes a certain number of hours later. Along the eastern coast of New England, for instance, the time of high tide is about eleven and one-third hours after the Moon's culmination, so that it happens little more than an hour before the next culmination of the Moon (340). Other irregularities in the tides, some of which are curious enough, are due to the fact that the Moon's orbit takes it sometimes north and sometimes south of the plane of the equator. This fact would naturally make a difference in the height of the two daily tides. When the Moon is north of the equator, for instance, we should expect the high tide due to its upper culmination to be higher in the northern hemisphere, and lower in the southern, than the high tide due to its lower culmination. This difference sometimes actually appears; but in many places it is made up for by the manner in which the tidal waves are combined with each other by the form of the coasts along which they sweep. A wave, as every one may observe for himself, may move quickly while the particular portions of water which form it at any one time are carried up and down, or forward and back, only a little; since the water which makes up the wave is constantly changing as the wave goes on. At the same time, when the wave is broad, like a tidal wave, however low it may be, it may give rise to strong currents, particularly in shallow water. On the coast of New England, each of the two daily tides is about as high as the other; while on the coast of California, one of them is usually large and the other small.

675. The reason why the Moon has so much more than any other celestial body to do with the tides is the same which accounts for its comparatively great effect in occasion-

ing precession (669). But the tides due to the Sun are large enough to be readily noticed; hence when the Sun and Moon are in conjunction or opposition, so that their effects are combined, the tides rise highest. This happens, of course, when the Moon is new or full. Since the tides of the eastern coast of New England are about eleven hours late (674), the eleven o'clock tide is the highest on that coast. About the time of half moon, the tides rise and fall comparatively little; they are sometimes called neap tides, while those which occur when the Moon is new or full are called spring tides.

676. The Moon's varying distance from the Earth makes a difference in the amount of the tides; a spring tide occurring when the Moon is in perigee will be unusually high.

## CHAPTER XV.

### HISTORY OF ASTRONOMY.

677. AT the present day, the progress of astronomical knowledge depends on ingenious instruments, accurate measurements, and intricate calculations. No one can obtain the means of forming an opinion of his own upon astronomical questions until he has fitted himself to consider them by learning how to use strict mathematical forms of reasoning, and how to apply his reasoning to actual observations. Most of us, who cannot spare time for the thorough study of astronomy, must be content to take for granted the correctness of any opinion generally held by educated astronomers on the subjects of their science; but we need not at once accept every new statement announced as an astronomical discovery, for many such statements prove to be mistakes. There is no way of preventing mistakes altogether, even among men who are distinguished in science. In fact, if the full history of astronomy, or of any other branch of knowledge, were recorded, we should find it to consist mainly of an account of mistakes. As it is sometimes written, however, it gives us the impression that the ancient astronomers did little but make mistakes, and that modern astronomers do little but discover truths. But this impression is scarcely fair. In our own times, many careless guesses are put forward as if they were part of science, just as similar guesses were put forward long ago. Indeed, people who have not learned astronomy sometimes undertake to speculate about astronomical subjects, and so waste a great deal of time in a way which is much more foolish than it would have been hundreds of years ago, when nothing was definitely known about any of the natural sciences. On the other hand, we find that in past ages, as well as in recent times, there have been men

who attentively observed the facts of nature, and tried to form reasonable judgments about the facts which they had observed. Even the mistakes of men of this kind are more creditable to them than any mere fancies could have been, admitting these fancies to have been correct.

678. Among the most remarkable fancies of mankind with regard to the stars was that from which arose the study of astrology. There is little difference in the original meaning of the words astrology and astronomy, and they were once both used to mean the study of the various celestial objects. For the past three centuries, however, and perhaps longer, astrology has been generally understood to mean only the attempt to foretell the course of human affairs by calculations founded on certain real or imaginary astronomical observations. No one who wishes to be considered sensible now pretends to think that this can be done; but in past times a great deal of study and ingenuity were laid out in drawing up rules for astrological inquiries.

679. The first astronomers of whose observations and theories we have any distinct account lived in the various Grecian settlements on the coast and on the islands of the Mediterranean Sea. Some attention seems to have been paid to astronomy in still more ancient times by the Egyptians and Chaldeans, and also in Hindostan and China; but little is known to have been learned by any early astronomers except the Greeks. We find in several of the Egyptian pyramids slanting passages leading downwards into the pyramids from their northern faces. The slant of these passages is such that the part of the sky seen by an observer at the lower end of one of them is about 4° below the north pole of the celestial sphere. These pyramids are supposed to have been built about four thousand years ago, and at that time the rather bright star $\alpha$ Draconis was within 4° of the pole, so that it could be seen from the passages just mentioned at its lower culmination. It is probable that the slant of the passages was designed to permit observations of this kind, although the use made of these observations is not known.

To make a fair estimate of the attainments of the early astronomers, and especially of the Grecian astronomers, we must notice how little is known about the stars by most people at the present day, and what astronomical facts can now be observed without the help of expensive instruments. While scarcely any one now knows any thing of these facts except what he has learned about them from books, most of them have been familiar to astronomers for the last two thousand years, and probably still longer: so that there must have been much interest in actual observation in very early times, although doubtless less than there now is among scientific men, since its usefulness has been clearly shown.

680. The first step in astronomy for an observer who has no instruments must consist in learning to recognize a considerable number of the bright stars. This may be done with a little patience by any one, even if he has no map or globe to tell him the names of the stars. It is all very well to know the name by which other people call some particular star; but after all, the knowledge of an observer with regard to that star consists in his being able to distinguish it from others; and he can give it a name of his own, if he likes, which will serve this purpose as well as any other name, so far as he is concerned; although when he has any thing to say about it to other people, he must use a name for it which they will understand.

681. The method of naming stars used among the Greeks was too cumbrous to be of any service in our times. The stars were arranged in fanciful groups, each supposed to represent the figure of some animate or inanimate object, and any particular star was named by its place in the figure to which it belonged (82). Sirius, however, and a few other stars, had names of their own. In later times many of the stars had special names among the Arabian astronomers, which are still sometimes used, although they have been oddly altered in their passage from the Arabic into European languages.

682. The groups, or constellations, in which the ancient

astronomers considered the stars as arranged, probably had at first no exact boundaries. Claudius Ptolemæus, or Ptolemy, as he is usually called, drew up the first list of fixed stars which has come down to our times. This astronomer lived at Alexandria in Egypt, about A.D. 140. On the system he employed, no star was regarded as belonging to a constellation unless it was within the boundaries of a figure representing that constellation, and distinct from other figures. The names of Ptolemy's constellations are still in the main retained; but according to Ptolemy's arrangement there were many stars which did not lie within the boundaries of any constellation. Later astronomers extended the limits of the constellations, and formed several new ones, so that every star might be within the boundaries of some constellation. By this change, a constellation came to mean merely a portion of the sky, and could no longer be considered as a figure formed by a group of stars.

683. No improvement was made in the method of naming stars till A.D. 1603, when a set of maps of the constellations was published by Bayer, a German. In these maps the stars of each constellation were distinguished from each other by letters, the first letters of the Greek alphabet being assigned to the brightest stars. This convenient practice is still in use.

684. About a century later, Flamsteed, an English astronomer, made a catalogue of stars in which the stars of each constellation were arranged in the order of their right ascension at the time of the catalogue. Flamsteed also arranged in the order of right ascension the stars of each constellation found in the catalogue of Hevelius (a German astronomer of about the same time), as well as those found in some earlier catalogues.

685. In our day, stars are not catalogued according to their constellations, but are arranged in order of right ascension throughout; and each star is distinguished from the rest merely by a statement of its right ascension and declination at some particular date. However, many stars are still

referred to in speech or writing by their names, letters, or numbers. When letters, or numbers showing the order of the stars in Flamsteed's catalogue, and that of Hevelius as arranged by Flamsteed, are used as names of stars, the names of the constellations have to be added. The names of the constellations used by astronomers who write in English are Latin words answering in most cases to the Greek names found in Ptolemy's catalogue. Thus $\alpha$ Tauri means the star Alpha of the constellation Taurus, also called Aldebaran; $\alpha$ Canis Majoris, or Alpha of the constellation Canis Major, is Sirius; 1 Pegasi means the first star of the constellation Pegasus in Flamsteed's catalogue; 51 Cephei (H.) means the fifty-first star of the constellation Cepheus from the catalogue of Hevelius arranged by Flamsteed. Stars may likewise be referred to by their numbers in modern catalogues; in that case the names of the constellations are not needed.

686. After learning to distinguish one star from another, an observer will be able to compare the brightness of each star he knows with that of any other. In the absence of any accurate photometers, such as are now used for this purpose, all that can be done is to classify the stars according to their brightness. The comparative brightness of the stars of Ptolemy's catalogue is expressed by what Ptolemy, and other astronomers after him, have called magnitude (81); each star being said to be of the first, second, third, fourth, fifth, or sixth magnitude. Since the invention of telescopes, many additional magnitudes are recognized.

687. The periodical changes of brightness in certain stars (98) seem to have escaped the observation of all the ancient astronomers. Fabricius, a Dutch astronomer, was the first to discover the variability of Mira, or $o$ Ceti; and this discovery was not made till 1596. But now that stars are known to vary, no instruments are needed to show the changes of brightness in Mira, Algol, and a few other stars.

688. In making measurements of the apparent places of the stars, the Greek astronomers followed the method which

has come down to us from them. They measured distances on the celestial sphere in fractions of great circles, dividing each circle into degrees and minutes of arc. Every one, even if he has no instruments, should accustom himself thus to estimate the apparent distances between stars, instead of using measures of length, as many people do, to express quantities which are really angles. The number of degrees in the angle or arc between two stars can be roughly determined by estimating the number of times that the arc would be contained in the circle of the horizon, which contains 360°, or in the upper 180° of any vertical circle, the meridian, for instance. If a celestial atlas or globe is at hand, the arc of a meridian between any two stars which have about the same right ascension can be learned at once; and when these stars can be recognized in the sky, the arc between them will serve as a standard for other estimates. Care must be taken to distinguish between great and small circles, and all measurements are to be made in fractions of a great circle (412). People without mathematical knowledge used in ancient times to talk of the Sun as a foot (for instance) in diameter, just as people like them do now-a-days. But the educated Grecian astronomers perfectly understood that the apparent diameter of the Sun, or of any object, is an angle and not a distance.

689. The diurnal movement (524) is the only one in which all the celestial objects take part. It may easily be observed without instruments, as we have seen (124), and every educated person should have got some practical knowledge of it. He should notice, for instance, if he lives in the northern hemisphere of the Earth, what fraction of the meridian is included between the north point of the horizon and the North Star. He should know the course of the equator on the celestial sphere, not merely from maps, but from his own observations.

690. The explanation of the diurnal motion generally received among the ancients was that of the crystal sphere already mentioned (126, 128). But the explanation of the

same facts by the rotation of the Earth was also undertaken much more than two thousand years ago. Neither of these explanations could then be shown to be correct; and the astronomers who maintained the view which is now generally accepted do not seem to have taken much trouble to contrive observations or experiments by which their theory could be tested. Little credit, therefore, can be given them for the accidental correctness of their guesses.

691. To show that the Sun is constantly lagging behind the other stars in their diurnal movement (322), it was only necessary to watch the rising and setting of different stars at different seasons of the year. These appearances were soon perceived to return yearly in the same order, and the prediction of them was considered an important part of astronomy, until astronomers learned to make more difficult and more valuable predictions. At some rather late period in the history of astronomy, which cannot, perhaps, be exactly determined, the names of heliacal, cosmical, and acronycal rising and setting came into use instead of longer names applied to like facts by the ancient astronomers. A star rises heliacally when it rises only just soon enough to be seen before sunrise, and sets heliacally when it sets so soon after sunset that it can barely be seen. Its cosmical rising happens when it rises exactly at the same time with the Sun, and when it rises just at sunset, the rising is acronycal. A star may set just at sunrise or just at sunset, but authorities differ as to which of these settings should be called cosmical, and which acronycal.

692. The ancient poets frequently mention the rising and setting of certain constellations without stating what kind of rising and setting they mean. It is only on this account that the preceding explanation is worth giving. The days of the heliacal setting and the acronycal rising of a star are likely in practice to be more frequently spoken of than the days of the other appearances above mentioned; since this setting and this rising happen early in the evening, when the stars are usually most noticed. The acronycal rising cannot be directly

seen ; but any star seen near the eastern horizon as soon as it is dark may be supposed to have risen about sunset.

693. Close observation of the heliacal settings and risings of stars apparently near the Sun will enable any one to trace out the Sun's course among the stars ; and this had been done, no doubt, before the time of the earliest astronomical records. It had been noticed, too, that the Sun pursued the same course year after year, so far as could be shown by rude observations. The belt of the sky marked out by the constellations through which this course passed was called the zodiac ; the course itself was recognized as a great circle of the celestial sphere, and the angle between its plane and that of the equator was pretty well determined. One common name for the Sun's course was the oblique circle, to distinguish it from the equator, the plane of which is perpendicular to the axis of the diurnal movement. In later times, the oblique circle got its present name of ecliptic from the circumstance that eclipses can happen only when the Moon is near the ecliptic. The width of the zodiac was set down as just 12° by some ancient astronomers. The ecliptic was divided into twelve arcs each of 30° ; these arcs were named after the twelve zodiacal constellations, and were afterwards called signs. These signs never corresponded to the constellations after which they were named, for some of the constellations take in more than 30° of longitude, and others less. Besides this, precession is always shifting the longitude of a constellation ; while the *sign* Aries, for example, always took in the first 30° of the ecliptic, counting from the vernal equinox. Modern astronomers have left off the practice of dividing the ecliptic into signs.

694. It is by no means a modern notion that the apparent movement of the Sun in the ecliptic is due to a yearly movement of the Earth round the Sun. Aristarchus of Samos, who lived over 2,100 years ago, certainly proposed this explanation, and answered the chief objection to it by the correct guess that the stars were so far from the Sun and Earth that no apparent change in their places could be occasioned by

the Earth's movements round the Sun. It shows how little can be done in science by guesswork alone, that the opinions of Aristarchus were not accepted by later astronomers, and were almost wholly forgotten for some eighteen hundred years. If Aristarchus had found out any system of calculation by means of which the apparent places of the planets could be readily foretold according to his theory, no educated astronomer would have afterwards considered the Earth as stationary. But it was not till about two hundred years later that Hipparchus succeeded in inventing a system of calculation by which predictions could be made much more correctly than had been practicable before his time. Hipparchus, who lived at Rhodes, about a century before the Christian era, seems to have invented instruments, as well as calculations, of new kinds, and to have been industrious in the use of all his inventions. He was the first, so far as is known, to make a catalogue of stars. Ptolemy's catalogue, indeed, is supposed to be merely a copy of that made by Hipparchus, altered enough to allow for what Ptolemy supposed to be the amount of precession since the date of the catalogue he copied. The fact of precession was known to Hipparchus as well as to Ptolemy; but even in Ptolemy's time, its amount had not been ascertained. Apparently Ptolemy might have done something to determine it if he had made more observations of his own and had compared his results carefully with those of Hipparchus. For want of this, his catalogue is not nearly correct for his own time.

695. The system of calculation employed by Hipparchus and his successors was founded on what we call trigonometry, a branch of mathematics which Hipparchus seems to have been the first to discover. His method, as might be expected, was clumsy, but it served its purpose. The theory to which it was applied seems not to have originated with Hipparchus, who adopted it from some of his predecessors. In this theory, the Earth was regarded as stationary, and the movements of celestial objects were resolved into circular movements variously combined. It was adopted and developed by

Ptolemy, and continued in use among astronomers until about two hundred and fifty years ago. When it is now mentioned, it is usually called the theory of epicycles. Connected with this theory were many suppositions about solid transparent spheres (like the sphere of the fixed stars) revolving within each other; but these suppositions, which were older than the time of Hipparchus, have in fact little to do with his system, which consisted in the mathematical combination of different movements.

696. It was probably unfortunate that Hipparchus did not apply his mathematical inventions to the theory of Aristarchus; but this mistake has not prevented him from being considered in modern times as the founder of the science of astronomy. His merit consisted not in guesswork, but in actual observation and in the invention of methods by which observations could be made available for predictions. These methods, indeed, furnished the means by which the defects of the theory of epicycles were at length made to appear.

697. Aristarchus himself seems to have been a good mathematician for the time at which he lived, and his actual observations and calculations were more valuable than the correct suppositions which he made without discovering the means of testing them. Hipparchus did so much to provide these means that the incorrectness of his theories was of comparatively little consequence.

698. Although the Earth might in ancient times be reasonably thought to be at rest, its globular shape could not be doubted by any attentive observer. The opinion prevalent among the Greek astronomers, indeed, seems to have been that the Earth is a sphere; and in later times, even when the disturbed political condition of Europe had produced the decline of civilization which for some centuries almost wholly checked the progress of natural science, many intelligent and educated men were aware that the Earth could not be flat. Any one who has occasion to travel a few hundred miles northward or southward, and who closely watches the stars during his journey, may see for himself that either the verti-

cal lines of the different places he travels through have different directions, or else the stars are so near that he actually passes by some of them on his way. But in this last case, if we travel northward, the southern stars ought to seem closer together than before; and if we travel southward, they ought to appear to spread apart, while the northern stars should draw together. In fact, however, we cannot produce any apparent movements of the stars among each other by our journeys on the Earth. Hence it no doubt became manifest in early times to careful observers that the stars must be at least so far away from the Earth as to make the lines drawn to any star from different terrestrial places too nearly parallel with each other to be distinguished from strictly parallel lines. Then, since the stars which daily pass near the zenith of one terrestrial place are not the same with those which daily pass near the zenith of a place some distance north or south of it, we are forced to conclude that the zeniths of the two places are in different directions from the Earth. Now this amounts to saying that the Earth is globular; for its surface seems on the whole to be everywhere horizontal, while yet any two places on that surface differ in their horizontal planes, as they must if the directions of their vertical lines are different. We see, too, that as we travel northward or southward the place of the zenith moves with us, not the contrary way, as it would if the Earth's surface were hollowed out, or cup-shaped. We conclude, then, that it is everywhere globular, or at all events rounded off northwards and southwards. Although the diurnal motion of the stars makes it less easy to show directly that the Earth is rounded eastwards and westwards also, the very facts of this diurnal motion make it likely that such is the case. It is not surprising, then, that the ancient astronomers had a pretty correct notion of the shape of the Earth; but this notion of theirs shows that they were better observers than many educated people of modern times.

699. The size of the Earth, admitting it to be a sphere, can be judged of roughly by noticing how much travelling

northward or southward is required to shift the place of the zenith 1°; the simplest way of doing this is to observe the lengths of shadows at noon on the same day in two places nearly on the same meridian. The Greek astronomers had in fact obtained in this manner fair estimates of the length of a diameter of the Earth, but as they had no means of making accurate surveys of its surface, they were never able to do more than merely estimate this length.

700. Even in our time it is difficult to determine the distance of the Earth from other bodies, and it is not wonderful that the ancient astronomers had little success in their attempts to find the distance of the Sun. They learned, however, to regard the Sun as at least so far from the Earth, that in order to have its apparent diameter of about half a degree, its actual diameter must be several times longer than that of the Earth. To show this, they had only to compare the places of the ecliptic among the stars which result from observations made in different terrestrial places. As there is no noticeable difference between these places of the ecliptic, it follows that if the stars could be seen in the daytime, the Sun, as viewed at the same time by observers in different parts of the Earth, would seem to all the observers in the same place among the stars. Hence, if the Sun is nearer than the stars, it must at all events be far away compared with the distance between any two terrestrial places. This may have made the theory of Aristarchus seem very unlikely to his successors; for if the Sun was allowed to be so distant that it showed no parallax with respect to the stars, it would certainly seem strange that the yearly motion of the Earth round the Sun could take place without changing the apparent places of the stars with respect to each other.

701. Aristarchus tried to determine the comparative distance of the Sun and Moon from the Earth by reckoning from their apparent places at the moment of half moon, when the lines from the Moon to the Sun and to the Earth must be perpendicular to each other. But he could neither observe the time of half moon nor the places of the Sun and

Moon with the precision required to make this method useful. However, he supposed himself to have made his observations accurately enough to warrant the conclusion that the Sun was from eighteen to twenty times as far away as the Moon.

702. The distance of the Moon could be most satisfactorily determined in ancient times by the comparison of observations of some eclipse of the Sun as seen from different places. It must soon have been noticed that no eclipse of the Sun was total in all terrestrial places; and that some distance north of the place where an eclipse appears total, the northern part of the Sun is seen beyond the Moon, while the southern part is visible at places far to the south. Hipparchus was enabled, by his improvements in mathematics, to calculate the Moon's distance from the observations made at Alexandria and on the Hellespont of a remarkable solar eclipse. The observations were not precise enough to give a result very close to the truth, except by accident; but Hipparchus concluded that assuming the Sun's parallax to be small, the distance of the Moon was about seventy-seven times the semidiameter, or radius, of the Earth (sixty times would have been nearer right, and in fact other determinations attributed to Hipparchus range from about sixty to about eighty). Ptolemy proposed a method of finding the Moon's parallax by observing its zenith distance at the time of its culmination, and comparing this observed zenith distance with the zenith distance calculated for the time of the observation from the observer's latitude and the supposed orbit of the Moon. The instrument contrived for the observation consisted of an upright standard, carrying a movable arm with sights through which the Moon was observed. The uprightness of the standard was tested by a plumb-line hung beside it. The angle formed by the standard and the arm, which were of equal length, was measured by divisions on a second arm jointed to the lower end of the standard. This instrument could not give precise results, and the facts required for the calculation of the Moon's geocentric place were ill-determined in Ptolemy's time. Hence his conclu-

sions are untrustworthy, although the result he reports is not far wrong; but both Hipparchus and Ptolemy supposed the distance between the Earth and Moon to vary much more than it really does. Instruments of the kind just mentioned were sometimes used by later astronomers. They were called parallactic rules, and also "Ptolemy's rules." Modern astronomers imitate Ptolemy in determining parallax from zenith distances observed on the meridian; but when the Moon's parallax is thus to be determined, numerous observations are made at each of two places far distant from each other.

703. Another instrument used by Ptolemy, and probably invented by Hipparchus, was the astrolabe, a combination of graduated circles provided with sights, which was mainly used in measuring celestial latitudes and longitudes. The name of astrolabe has also been applied to a simpler instrument used in taking altitudes.

704. The best ancient time-keepers were water-clocks. These are vessels out of which, or into which, water is allowed to leak through small openings. Water-clocks of the first kind are usually called clepsydræ; they were used extensively by the Greeks and Romans. Water-clocks of the second kind were used in Hindostan. By the time required to empty or fill the vessel, as the case may be, the day may be measured off into parts of about equal length.

705. An upright pillar, or gnomon, was anciently an astronomical instrument of some value. It showed the comparative length of the shortest shadows on different days in the year; and in this way the length of the tropical year itself, and the differences of latitude of different places, could be tolerably well made out (699).

706. Little progress was made in any of the natural sciences for nearly fourteen hundred years after Ptolemy's time. For several centuries after the great conquests of the Arabs and the other Mahometan nations, there was more scientific study among them than anywhere else; but although many of their astronomers showed some talent, they made little improvement in the astronomy of the Greeks.

Their recorded observations have at times been serviceable to modern astronomers, and they did something to improve the methods of calculation invented by Hipparchus and Ptolemy.

707. From time to time, attempts were made to correct the suppositions on which astronomical predictions were founded. These suppositions related to the extent and rate of the various circular motions into which those of celestial objects were resolved; and their chief results drawn up in systematic form, so as to be useful in computation, were called tables. The first astrononomical tables which seem to have been drawn up in Europe were those called the Alphonsine Tables, after Alphonso X. of Castile, who employed the best astronomers of his time in their construction. Alphonso reigned in the last half of the thirteenth century.

708. About two hundred years later, the German astronomer Regiomontanus undertook the construction of a calendar containing astronomical predictions for several years to come. Calendars, in this sense of the word, or ephemerides, as they are now frequently called, differ from tables in giving the predictions of particular events which can be observed, while tables give the materials for the construction of predictions. The predictions of Regiomontanus were good considering the faulty theory on which they were founded; but the time had now come for this theory to be questioned.

709. Copernicus, who lived in the first half of the sixteenth century, reinvented and extended the theory of Aristarchus. By regarding all the planets, including the Earth, as revolving about the Sun, while he considered the Moon as accompanying the Earth in its revolution, and at the same time revolving about it, he materially simplified the theory of astronomy. The phenomena of precession were also explained on right principles by Copernicus. He did not succeed, however, in removing the difficulties of the old system of astronomy; for he supposed the orbits of the planets to be circular, and was therefore obliged, like the ancients, to account for the results of observation by complicated combinations of circular movements.

710. Towards the end of the same century, Tycho Brahé made a long and accurate series of astronomical observations on an island near Copenhagen. His reputation as an astronomer depends on these observations; his theories were not important. But his observations furnished the means by which an astronomical discovery, more important than any which had been made since the time of Hipparchus, was to be brought about. Tycho Brahé was obliged, towards the close of his life, to withdraw from Denmark, in consequence of the ill-will of persons of influence at the Danish court. He removed to Prague, where he became acquainted with Kepler.

711. The recorded observations of Tycho Brahé enabled Kepler to discover his three celebrated laws. This discovery was no mere guess; although Kepler made many fanciful guesses, he was ready and able to test his guesses by the difficult calculations required for the purpose of comparing their results with those of actual observation; and when he found that either a guess or an observation must be wrong, he did not insist, like many fanciful people, that the error lay in the observation. His theory, when it was finally made out, enabled him successfully to represent the apparent movements of Mars (the planet to which his work was mainly confined) by two elliptical movements, one attributed to the Earth and the other to Mars; the speed of these movements being determined by the law that the radius vector of each planet passed over equal areas in equal times. This discovery put an end to the need of attributing various circular movements to a single planet.

712. The value of Kepler's work lay in what he proved, not in what he conjectured. If his guesses had been valuable in themselves, he would be considered one of the chief inventors of the laws of motion now accepted, including the law of gravitation. He supposed that material objects attracted each other, but he could not show exactly how they attracted each other. His really important discoveries were not at once recognized among the numerous vague speculations with which he had filled his writings; and in his own time

the great improvement which he had made in the theory of Copernicus seems to have passed unnoticed.

713. Besides discovering the laws of planetary motion, Kepler also took part in the great discovery of the telescope, which was made in his times. He seems to have been the first to describe that combination of two convex lenses the principle of which is now in universal use in astronomical instruments. He also improved the theory of astronomical refraction.

714. In a treatise on optics, by Ptolemy, the fact of refraction by the air is noticed and explained on right principles. The fact, too, that the eclipsed Moon may sometimes be seen in the east before sunset was noticed in ancient times, and its explanation by the theory of refraction was attempted. Still, the Greek astronomers never learned much about refraction. The Arabic astronomers studied it to some extent, and Tycho Brahé, as well as other astronomers, had also attended to its effects. Kepler drew up empirical rules for calculating refraction, which gave nearly correct results, except close to the horizon, where even the rules of modern astronomers are often at fault, on account of the great variations in the state of the lower parts of the Earth's atmosphere.

715. The work in which Kepler stated his first and second laws of planetary motion appeared in 1609; he stated his third law in a work published ten years later. Some writers prefer to arrange these laws in one order, some in another; the arrangement given above (150) seems on the whole most conformable to the course of Kepler's reasonings, although the general principle of the second law seems to have occurred to him before he had assigned elliptic orbits to the planets.

716. We may consider the rapid progress of physical science, which forms one of the most noticeable parts of modern history, to have begun about the time at which Kepler lived. The number of men who did valuable work in science became so large during the seventeenth century

that it is impossible in any short account of the progress of astronomy to name more than a few even of those who attained the most important astronomical results. Galileo, a celebrated Italian, contemporary with Kepler, by his experiments in mechanics, greatly assisted in the discovery of our present laws of motion. He was the first, also, to make astronomical discoveries by means of the telescope. Having heard, in 1609, of the accidental invention of magnifying instruments in Holland, he found little difficulty in discovering, on known principles of optics and geometry, one of the plans on which telescopes may be constructed. This plan is that on which each of the telescopes of an opera-glass is now made; it is not in use in astronomical telescopes. Galileo discovered the satellites of Jupiter and observed spots on the Sun with telescopes of his own construction; he also saw that there were projections on each side of Saturn, but his instrument did not show the ring distinctly.

717 Huygens, about fifty years later, made considerable improvements in telescopes and in clocks. No achromatic telescope had yet been made, and in order to obtain more magnifying power than that of former telescopes, without blurring the image, Huygens had to use object-glasses of greater focal length than is now given even to the largest lenses. Some of his telescopes had no tubes, their object-glasses being mounted separately from their eye-pieces. Huygens was born at Amsterdam, but passed much time in France and England. He discovered the ring of Saturn and one of its satellites, and observed the rotation of Mars.

718. Picard, a French contemporary of Huygens, combined the telescope with graduated arcs for making measurements in the modern manner. In 1670 he determined the Earth's diameter far more exactly than had been previously done. For this purpose, he carefully measured a base line near Paris, from which he surveyed the country between Sourdon, near Amiens, and Malvoisine, near Paris; these were his two astronomical stations. He measured the least zenith distance at each station of a star in the constellation

Cassiopeia. The difference of these zenith distances, each of which was found by a great number of observations, gave him the angle formed by the vertical lines drawn in the plane of a meridian from two points, one in the latitude of Sourdon, and the other in that of Malvoisine. His survey gave him the distance along a meridian between these points. This distance was the length of that fraction of the whole meridian which was contained in the circumference of the Earth as many times as the angle to which it had been found to answer was contained in 360°.

719. Four or five years before Picard's measurements, the celebrated English philosopher, Newton, had correctly guessed the law of gravitation; that is, he had conjectured, not that bodies attract each other, which was an old guess, but according to what rule they move towards each other. But he had not published his guess, and given it out as a great discovery. He had set himself to calculating how quickly the Moon ought, under this rule and the law of inertia, to move round the Earth. The number of times which the Earth's diameter was contained in the Moon's distance had by this time been tolerably well settled, so that Newton knew pretty nearly the length of its orbit with respect to the Earth. But he employed in his calculations an estimate of the Earth's diameter which happened to be considerably too small. Hence, in his calculations, the Moon seemed to move slower than it really does, or that it should according to the law at which Newton had guessed; for as he supposed the Moon's distance from the Earth to be less than it is, the number of miles it travels monthly with respect to the Earth is greater than he supposed. If Newton had been a practical astronomer, this would have set him to measuring the Earth. But he had many scientific occupations besides his inquiry into the Moon's movements, and he was not an astronomer by profession. Under like circumstances, many men would have published their guesses and calculations in order to claim the discovery of the law of gravitation if the Earth's diameter turned out afterwards to be longer than had

been supposed. Newton simply put the inquiry aside and turned his attention to other matters.

720. The results of Picard's survey and latitude observations do not seem to have attracted Newton's attention. He was apparently led to resume his inquiries concerning the law of gravitation by the progress of similar inquiries among other philosophers. One of his contemporaries, Dr. Hooke, had proposed a theory of gravitation in 1674; and in 1679, Hooke suggested that if the force of gravitation was inversely proportional to the square of the distance between two bodies on which it acted, one body would circulate in an ellipse about the other. We see, then, that Hooke had guessed the law of gravitation itself. But he either could not prove his guess for want of mathematical power, or at all events he neglected to prove it.

721. Admitting the law of gravitation to be true, it was easy enough to show, as has been shown above, that it would account for Kepler's second law, and also for his third law, on the supposition that the orbits of the planets were circular. But the science of mathematics was not yet sufficiently developed to permit Kepler's first law to be readily reconciled with the other two under the law of gravitation. This was the problem which could be solved only by the genius of Newton. The greatness of his discovery consisted not in guessing the law of gravitation, for that could be done by others, but in proving what the consequences of such a law would be.

722. It seems that about the year 1679 he found out how to prove that two bodies moving under the laws of gravitation and of inertia, might circulate about each other in elliptic orbits. But then, being still unaware, perhaps, of the results of Picard's work, he again dropped the subject; so that we owe the completion of his work only in part to him, and in part also to the discoverer of Newton's discovery. This discoverer was the English astronomer Halley. Like Newton, Hooke, and other philosophers of his time, he had been looking for general rules which would account for

Kepler's laws. He had discussed the subject with Hooke, and as Hooke could not or did not show how elliptic movements might follow from the law of gravitation, Halley visited Newton, whom he knew to be a distinguished mathematician, and asked him what he thought would be the path of a body moving about another under a law like that of gravitation. Newton replied that he had proved that this path might be elliptic. Halley recognized the importance of the discovery, urged Newton to complete his work, and took the expense of its publication upon himself.

723. Newton's Principia appeared in 1687, three years after the above-mentioned visit of Halley. The general laws of motion laid down in the Principia were before long almost universally accepted, and have served ever since as the basis of astronomical calculations. But the importance of the work does not consist in the mere statement of these laws; it consists in the mathematical process by which they are applied to the resolution of the movements of celestial objects into rectilinear movements (599).

724. In the following century many illustrious mathematicians and astronomers carried on the work begun by Newton, which may be said, in a certain sense, to have been completed early in the present century by Laplace, in France, and by Gauss, in Germany. These writers brought into systematic form the results of investigations made by themselves and their predecessors, which enable the astronomers of the present day to account completely for those movements of the celestial bodies which were known in the time of Newton. But modern astronomical improvements have brought into notice so many new facts, that the process of explaining observed movements by the mathematical development of the laws of motion is as far as ever from coming to an end. It may be noticed as a curious fact that the movement called the secular acceleration of the Moon, which Laplace supposed himself to have wholly accounted for, is now considered to be only partly due to the causes proposed by him. Recent inquirers attribute the rest of this secular

acceleration to a gradual slackening of the Earth's rotation, which is itself accounted for by the action of the tides. But the period of the Earth's rotation is thus so slowly lengthened, that, according to one estimate, it is now only about a second longer than it was eighty thousand years ago.

725. Newton distinguished himself in optics almost as much as in mechanics. His experiments on light showed for the first time that different kinds of light differ in refrangibility. He discovered the principle of the sextant, though he never published this discovery; and he was the first to make a reflecting telescope, although the principle of the instrument had been previously known. Reflecting telescopes were improved in the next century, towards the close of which Sir William Herschel made reflectors more powerful than any other telescopes of his time. With these, he made numerous additions to our knowledge of the planets, one of which, Uranus, was first noticed by him, although it had been seen by others, who took it to be a star. Sir William Herschel, too, was the first to show that some of the double stars are binary stars. Achromatic lenses were brought into notice by Dollond near the middle of the eighteenth century, and since manufacturers have become able to make large disks of glass, from which powerful achromatic combinations of lenses may be formed, refracting telescopes have been generally preferred to reflectors. It is not long, however, since Lord Rosse built great reflectors, the speculum of one of them being six feet across; and still more recently, a large reflector has been mounted at the Observatory at Melbourne, Australia.

726. The velocity of light and the distance of the Sun are subjects so connected with each other that the discoveries made respecting them may be jointly considered. If we know the Sun's distance, we know the length of the Earth's orbit, and can calculate what differences of aberration (551) will result from the rate of our movement round the Sun compared with the rate at which light moves. This last rate may then be determined by observing the annual aberration

of the stars (555). Again, if we know the Sun's distance, we can determine the velocity of light by the times of the eclipses of Jupiter's satellites; for when Jupiter is in opposition, its distance from the Earth is less than it is when Jupiter is in conjunction, by about twice the Earth's mean distance from the Sun. Now by repeatedly observing Jupiter for a few days at a time, the rate at which its satellites move round it may be noticed, and Tables (707) of their motion may be formed. Hence the times of their eclipses may be predicted without regard to the velocity of light. If these predictions are made right for the time when Jupiter is in opposition, the eclipses of Jupiter's satellites will be observed at other times later than they should be according to prediction; and the time required for light to cross the Earth's orbit may thus be ascertained. If, then, the width of this orbit is known, we may find the velocity of light.

727. On the other hand, if we know the velocity of light, we may reverse either of these processes, and thus find the Sun's distance.

728. The usual way of finding the Sun's distance without knowing the velocity of light is, as we have seen, to find the distance of Venus or Mars, by means of the parallax of either of these planets; then, by Kepler's third law, the times of the sidereal revolutions of the planets will determine their respective distances from the Sun.

729. Although Tycho Brahé's observations of Mars were much better than those of earlier astronomers, Kepler could not accurately determine from them the planet's parallax. With the instruments contrived by Picard (718), observations could be made far more accurately than in Tycho's time; and observations of the parallax of Mars were made with tolerable success in 1672 by Picard, Roemer, and Cassini in France, and by Richer at the island of Cayenne, about 5° north of the equator. On Richer's return to France, his observations, with those of the observers at French stations, were discussed by Cassini, who concluded the parallax to be such as to make the distance of the Sun nearly what we now

consider it to be. This good result was mainly accidental, for the observations made were not accurate enough to warrant any precise conclusion; but since they were numerous, their mistakes were likely to balance each other sufficiently to give a tolerably correct parallax. Richer made various other observations at Cayenne besides those of the place of Mars; and he noticed that the pendulum of a clock which went correctly in France had to be slightly shortened to keep the clock from running slow at Cayenne. This was the first direct experiment which tended to show that the general laws of motion require us to regard the Earth as having a movement of rotation (160). The still more direct proofs of this conclusion by means of experiments with the free pendulum (130), and with the gyroscope (133), were contrived in 1851 and 1852 by Foucault.

730. A few years after Richer's voyage, Roemer noticed that the observed times of the eclipses of Jupiter's satellites could be best explained on the supposition that light required time to come from an object to the observer's eye; but he seems not to have followed out this line of research very thoroughly.

731. The transits of Venus in 1631 and 1639 had passed without being used for observations of parallax, which would indeed have scarcely been practicable at that period. Kepler predicted the transit of 1631; his Tables were not sufficiently correct to predict the transit of 1639, which was observed, however, in England by Horrocks and Crabtree. Kepler was aware that there would again be a transit of Venus in 1761, and Halley, in one of his astronomical works, called the attention of astronomers to this transit, and pointed out a method of obtaining from it a correct determination of parallax by means of the observed duration of the transit as seen from different terrestrial stations. It is obvious, for instance, that if an observer in the northern hemisphere sees the planet pass over the centre of the Sun's disk, an observer in the southern hemisphere will see the planet pass north of the centre of the disk; and therefore that the visual angle between

the lines from the extremities of its path across the disk will be less than the corresponding angle through which the first observer sees it pass. It does not follow that the duration of the transit seen by the first observer will be greater than that seen by the second; for this duration partly depends on the speed with which the observer is carried along by the Earth's rotation, which usually tends to shorten the transit, since the planet's movement at its inferior conjunction is retrograde, while that of the Earth's rotation is direct. We must therefore take the exact latitudes of the observers into account; by doing this, we may calculate, from their observations of the duration of the transit, how much farther from the centre of the Sun's disk the planet seemed to one observer than it seemed to the other, in the middle of its transit. This will show the relative parallax of Venus and the Sun.

732. The transits of Venus occur in June or in December; this depends, of course, on the place of the nodes of the planet's orbit, since the planet must be nearly in the plane of the ecliptic in order that it may come between the Earth and the Sun. Since its transits happen when the Sun is constantly in sight from either the arctic or the antarctic regions of the Earth, an observer may be stationed so as to look at a transit of Venus about the time of the lower culmination of the Sun; and in this case, the transit will be prolonged, instead of being shortened, by the effect of the Earth's rotation.

733. Since the Earth's rotation during a transit of Venus always changes the place of an observer, not stationed at one of the poles, with respect to the line joining the centres of Venus and the Earth, observations of the transit made in only one terrestrial place may be used in calculating parallax. So, too, when the apparent place of Mars is compared with those of stars nearly in a line with it, its parallax may be determined by observations in one place at different times of night. But in order to obtain the best possible results, observations made in different places must be compared together. Halley, as has been said, proposed a system of

calculating parallax from the differences of the durations of a transit at different places ; those places at which, as compared with others, the transit occupies a decidedly long or a decidedly short time being the most advantageous stations for observing it. Another method, proposed by Delisle, does not absolutely require the observation at each place of both the beginning and the end of the transit. It depends on the comparison of the times at which the transit begins or ends in different places. But this method supposes the longitudes of these places to be very well known.

NOTE. — For the last sentence of section 731, substitute the following sentence: This will enable us, since we already know the relative distance of Venus and the Sun, to calculate the parallax and the distance of either.

and combined with others made in Europe. The parallax of the Sun may be directly obtained from its zenith distances when it culminates at different terrestrial stations ; the zenith distances of stars being also observed at these stations. There will be no difference due to parallax between the apparent places of the stars observed at different places, while there will be some difference of this kind in the case of the Sun ; but this method is not very exact. However, La Caille's determination of the Sun's distance, by all his various methods, was more trustworthy than any previously obtained, although it differed more than the determination of Cassini from that now considered correct.

735. In observing the transits of 1761 and 1769 nothing was attempted of importance, except to note the precise moments at which the planet seemed to the observer to have completely entered upon the Sun's disk, and at which it began to quit the disk at the close of the transit. The latitudes and longitudes of the places of observation were of course determined

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734. Before the time for the transits of 1761 and 1769, the movements of all the planets had been much better determined than they had been in the previous century, so that the time at which the transits would be seen could be well calculated, although not as well as the time of the transits of 1874 and 1882 could be calculated a hundred years later. Meanwhile, the parallax of Mars, of Venus near its inferior conjunction, and of the Sun, had been computed by La Caille from observations of his own, made at the Cape of Good Hope, and combined with others made in Europe. The parallax of the Sun may be directly obtained from its zenith distances when it culminates at different terrestrial stations ; the zenith distances of stars being also observed at these stations. There will be no difference due to parallax between the apparent places of the stars observed at different places, while there will be some difference of this kind in the case of the Sun ; but this method is not very exact. However, La Caille's determination of the Sun's distance, by all his various methods, was more trustworthy than any previously obtained, although it differed more than the determination of Cassini from that now considered correct.

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as well as might be. But it was found unexpectedly difficult to tell when the planet ought to be regarded as just within the border of the disk. Instead of appearing at this time as a round black spot, it seemed pear-shaped, as if it were attached to the limb of the Sun, after crossing it, by an elastic fastening. When this "black drop" broke and disappeared, the planet looked circular, but seemed to be already somewhat within the Sun's limb. As it approached the part of the limb where it was to quit the disk, a like distortion took place, so that the observers found it as difficult to determine the exact time of the end of the transit as to determine exactly when it began. Irradiation is regarded as the cause of the perplexing appearance just described.

736. From this and other causes, no result of importance was obtained from the observations of the transit of 1761. The result of the observations of 1769 was much better, although the moments of the beginning and end of the transit witnessed by each observer were again rendered to some extent uncertain by the effects of irradiation. The discussion which arose as to the right result to be obtained from these observations has lasted to our own time. Still, the transit of 1769 showed conclusively that the mean distance of the Earth from the Sun is from ninety to one hundred millions of miles.

737. Among the most important of the expeditions undertaken for the observation of the transit of 1769, were the English expedition to Tahiti (under the command of the celebrated explorer, Captain Cook), the Danish expedition to Lapland, and a French expedition to California. An observation at Pondicherry, in India, which was to have been made by the French astronomer Le Gentil, was prevented by clouds; and this failure must have been unusually annoying to the observer, as he had stayed eight years in the East Indies for the purpose of observing the transit. He had originally intended to observe the transit of 1761 at Pondicherry, but, owing to a war which was then going on between the French and English, in the East Indies, he had been

obliged, on that occasion, to remain at sea, where he saw the transit without being able to observe it to any good purpose.

738. In the present century, a great variety of means have been tried to determine the Sun's distance; among the chief of these are observations on Mars. The best observations for the parallax of Mars are those taken at stations differing considerably in latitude, but little in longitude, so that the planet may be observed at about the same time, and under like circumstances, at each station. But observations made at a single station early and late in the night are also serviceable (733).

739. It was not until recently that any determination could be made of the velocity of light, independent of the Sun's distance (727). The English astronomer Bradley discovered the facts of aberration (and also of nutation) by observations of the zenith distances of stars, made during the last century. Bradley was also the first to make observations of the stars accurate enough to serve as a means of determining proper motion. But although the observed aberration of the stars, and the observed eclipses of Jupiter's satellites, show the time required (about eight minutes) for the passage of light over a distance equal to that between the Earth and the Sun, we still require the knowledge of this distance to determine the velocity of light. In the present century, however, means have been found for the direct measurement of the rate at which light moves. Experiments on the velocity of light have lately been made by Cornu; their results were announced in 1873. They were made at Paris with an apparatus similar to one which had been contrived and used in 1849 by Fizeau, several refinements, however, being introduced into the work.

740. The general principle of these experiments is as follows: let the light of a lamp near the observer be reflected back to him from a distant mirror. Place a wheel near the observer and the lamp, so that the light goes to the mirror between the spokes of this wheel, and returns to the eye after again passing between these spokes. We will suppose

that the distance from the wheel to the mirror is half a mile; the light, accordingly, travels one mile between its first and second passages through the wheel. Let the spokes of the wheel taper towards the centre, and be everywhere just as wide as the spaces between them at the same distance from the centre of the wheel. Now if the wheel is turned at such a rate that the spokes, at the instant of the return of any particular part of the light, have just taken the places occupied by the openings through which that light went out to the mirror, it will be kept from reaching the eye, provided it comes back exactly in the opposite direction from that in which it went out. Hence, if each spoke moves through its own width in the time taken by light to go one mile, the observer will see no reflection at all; the wheel will act as an opaque screen. If the rate of its revolution is known, when this effect is produced, the speed at which light travels through the air may be calculated.

741. In practice, the light which is to be reflected must be reduced by suitable lenses to a small beam composed of pencils each of which is a nearly parallel pencil (435). The general direction of this beam is that of a line perpendicular to the distant mirror from the observer's eye, so that it comes back in exactly the opposite direction. It may seem as if this could not be done without setting the lamp exactly in front of the observer or behind him; but the lamp may stand at one side, and part of its light may be turned into the right direction by a slanting piece of glass through which the observer sees the returning light. The light goes out between the teeth on the edge of a wheel, which may be made to turn by mechanical contrivances as much as eight hundred times in a single second, if necessary; these teeth answer, since the beam of light is small, instead of the spokes we supposed the wheel to have. Assuming that the number of teeth is two hundred and fifty, it will take only $\frac{1}{500}$ of one revolution of the wheel to move the teeth into the places of the openings between them. If the wheel turns four hundred times in a second, $\frac{1}{500}$ of one revolution will

take only $\frac{1}{200,000}$ part of a second; and as light moves less than two hundred thousand miles a second, four hundred revolutions of the wheel in a second are even too many for the object of making the light disappear, if, as we have supposed, the wheel is half a mile from the distant mirror. In fact, if the wheel is at first turned slowly, and if its speed is gradually increased, the reflected light seen by the observer becomes dimmer, disappears when the wheel has attained a certain speed, and afterwards comes into view again, reaching its full brightness when the wheel turns twice as fast as at the time of the disappearance of the light. By continuing to increase the speed of the wheel, the light may be made to disappear again. The rate at which the wheel turns, and the signals by which the observer marks the disappearances and reappearances of the light, may be registered by electric apparatus. As the theory of refraction requires us to suppose slight differences in the speed of light through media of different refracting powers, the speed of light outside of the atmosphere must be calculated by known rules from its speed within the atmosphere determined by the experiments just described.

742. In Cornu's recent experiments, the wheel was about 10,310 metres, or nearly six and a half miles, from the distant mirror, which of course made the experiments easier and more trustworthy than they would have been if the distance had been small. Their result is that light moves beyond the atmosphere at the rate of 298,500 kilometres, or about 185,500 miles, in one second. The distance of the Sun, calculated from this velocity (727), agrees with the results of recent observations of parallax.

743. It is expected that the results of the observations of the transits of Venus in 1874 and 1882 will considerably increase the accuracy of our knowledge of the Sun's distance. It will be shown in the following chapter that our knowledge of this distance, on which our knowledge of all greater distances depends, is as yet far from accurate. Expeditions have been fitted out by the chief civilized nations

for the observation of the transit of 1874 at all available places which are also advantageous for such observations. The observers who are to note the times at which the transit begins and ends have been exercised in the observation of artificial imitations of the transit, so that they may be familiar with the deceptive effects of irradiation. But we have now other kinds of observations to rely upon. Numerous photographs of the Sun will be taken during the transit, and the place of the planet on the disk at particular times and stations will be determined by the measurement of these photographs. Measures of the planet's place will also be made during the transit with instruments known as heliometers. A heliometer is a telescope with its object-glass cut in two, the parts being made to slide upon each other so that two images of any observed object are formed, one of which can be brought to apparent coincidence with one of the images of some other object. The amount of movement of the two parts of the object-glass with respect to each other which is needed to bring about this coincidence serves to measure the visual angle between the objects.

744. The expeditions sent out by the United States occupy stations in China, Asiatic Russia, and Japan, in the northern hemisphere, and various islands in the southern hemisphere. English, French, German, and Russian expeditions occupy similar situations in various parts of the Earth. The transit occurs December 8, after midnight in Greenwich astronomical mean time, and hence December 9 in civil time.

745. The transit of 1882 will be visible along the eastern coast of the United States. It happens on the afternoon of December 6 in Greenwich time.

746. Closely connected with the subjects of the distance of the Sun and of the speed of light is that of the distances of the stars. No star was proved to have a noticeable parallax before the present century; but Bradley's discovery of aberration, and Herschel's of the existence of binary stars, had their origin in attempts to determine parallax. In 1838, the

parallax of a star in the constellation Cygnus (61 Cygni) was determined by Bessel, who had been comparing the apparent place of that star with those of others near it by means of a heliometer. Soon afterwards appeared Henderson's announcement that the chief star of the Centaur ($\alpha$ Centauri) showed a parallax amounting to nearly 1″. That is, the apparent places of this star, as seen at any time from the Sun and from the Earth, would differ by about 1″, or the $\frac{1}{1,296,000}$ part of the horizon or any other great circle of the celestial sphere. This is the greatest parallax yet discovered in any star; but, great as it is, it shows, as has been said (559), that the star is over two hundred thousand times as far from us as the Sun is; so that, as light takes about eight minutes to come to us from the Sun, it must take over one million six hundred thousand minutes, or more than three years, to come from $\alpha$ Centauri. Since 1838, many stars have been proved to have some parallax.

747. Various parts of the Earth have been surveyed, both in the last century and in this, with a precision much beyond what was possible in Picard's time. In this way the shape of the Earth has been shown to be very nearly in accordance with that assigned to it by an estimate of Newton's. One of the best computations of the figure of the Earth is that made by the distinguished German astronomer Bessel (the discoverer of the parallax of 61 Cygni) from his own observations and those of others. Bessel also did much to advance our knowledge of the proper motions of stars by accurately determining their apparent places. But this investigation has little interest except to professional astronomers, since the results to be obtained from it are yet distant. The apparent places of stars, however, are of constant use in all operations undertaken by astronomers and surveyors.

748. Perhaps the most remarkable astronomical discovery of this century was that of the planet Neptune, the apparent place of which was correctly predicted by Le Verrier in France, and by Adams in England, merely by means of the perturbations it had been producing in the movements of Uranus. It

was discovered, by means of the prediction of Le Verrier, in 1846. The discovery of asteroids began about the beginning of this century, and of late has gone on with great rapidity.

749. The researches in optics, to which we owe all the discoveries made with the spectroscope, began with the observation of dark lines in the solar spectrum by Wollaston, in 1802. The discovery was due to the use of a slit to admit the light, instead of a round opening, such as Newton used in his experiments on the refraction of light. But the experiments of Kirchhoff and Bunsen, about 1860, were those from which resulted the great interest and the rapid progress of spectroscopic work at the present day.

750. One of the first uses made of astronomical observations was their application to the measurement of time. The ancient Greeks and Romans were in the habit of dividing the time from sunrise to sunset into twelve hours, and the night likewise into twelve hours. These hours, accordingly, had no fixed length, but varied according to the season of the year. This was of no great importance for ordinary purposes; but the impossibility of making an exact year out of any whole number of days gave the ancients much trouble. The Egyptians decided on calling three hundred and sixty-five days a year, and dividing these days into twelve months of thirty days each, with five days between the end of the twelfth month and the beginning of the first month of the next year. This was a systematic method, very convenient in keeping account of time, but according to which each legal, or civil, year began a little earlier in the tropical year than the preceding civil year had begun. Accordingly, the Egyptian civil year began in all seasons, one after another, until finally the civil year began at about the same time in the tropical year as it did 1,460 tropical years or 1,461 civil years before. This length of time is sometimes called the Sothiac period. A period, in this sense of the word, or a cycle, which is a name of like meaning, is that length of time at the beginning and end of which different ways of measuring time agree. The agreement, of course, is seldom exact.

751. The Greeks tried to count time by lunations, and also by tropical years. Their actual reckoning was consequently in accordance with neither. The Athenians are said to have decreed public honors to Meton, who pointed out that the time occupied by two hundred and thirty-five lunations differs little from that occupied by nineteen tropical years; a discovery which seems to us of little consequence, because we no longer try to keep time by lunations. The period of nineteen years is called the lunar cycle, or the Metonic cycle.

752. There is another lunar cycle which is nearly equal to that just mentioned. During two hundred and twenty-three lunations, the line of nodes of the Moon's orbit has retrograded nearly nineteen times 360° with respect to the line joining the Earth and Sun. In other words, nineteen synodical revolutions of the Moon's nodes answer to two hundred and twenty-three synodical revolutions of the Moon. No one, of course, ever counted time by the movements of the imaginary points called nodes; but since eclipses of the Sun take place only when the Moon is near the plane of the ecliptic (or, in other words, near one of the nodes of its orbit) at the time of its conjunction, and eclipses of the Moon happen only when the Moon is in opposition, and near a node, the cycle just mentioned is a cycle of eclipses (370). That is, the eclipses which occur during any period comprising two hundred and twenty-three lunations follow each other at like intervals to those between the eclipses of the next two hundred and twenty-three lunations. As an eclipse of the Moon can be seen from any place at which the Moon is in sight at the time of the eclipse, it was noticed in very early times that each eclipse of the Moon was followed by another about eighteen years later, so that the eclipses of every eighteen years were repeated in the next eighteen years. Eclipses of the Moon could thus be predicted; but this simple method of prediction was not well suited to eclipses of the Sun, because an eclipse of the Sun can only be seen from that part of the Earth within the penumbra of the Moon.

This cycle of two hundred and twenty-three lunations, or about eighteen years, is sometimes called the Saros. It is not an exact cycle, so that it affords no precise means of making predictions.

753. Modern astronomers have noticed a number of cycles, like this cycle of eclipses, in the movements of various celestial objects; but all the effects which could be predicted by means of these cycles can be predicted more accurately by the general rules on which these cycles themselves depend. Five revolutions of Jupiter around the Sun pretty nearly correspond, for instance, to two of Saturn. Hence arises a peculiar disturbance of the movements of these planets, known as the great inequality of Jupiter and Saturn, which requires about 918 years for the production of its effects. During this time the conjunctions of Jupiter and Saturn have happened at a set of places pretty evenly distributed round the orbits of the two planets. Another cycle is that of the transits of Venus. Eight sidereal years take up about one day more than thirteen sidereal revolutions of Venus; while 235 sidereal years take up about $\frac{1}{16}$ of a day less than 382 sidereal revolutions of Venus. The nodical and sidereal revolutions of Venus are nearly of the same length (570). At any inferior conjunction of Venus, therefore, which happens eight years after one of its transits, the planet has nearly reached the same place it had when the transit occurred with respect to the node near which the transit occurred. At the inferior conjunction which happens 235 years after the transit, it is a little beyond the place it had when the transit occurred with respect to the node near which the transit occurred. These cycles cannot both be exact, since 8 is not contained an exact number of times in 235; and in fact, as has just been said, neither is perfectly exact. If the cycle of eight years were exact, and a transit had ever happened at one of the nodes, there would be a transit every eight years at that node. As it is, there are ordinarily two transits at the same node two days less than eight years apart, and then no more at that node till two days over 235 years from the last of the two transits.

The transits of 1631 and 1639 took place near the ascending node, or that at which Venus passes from south to north of the plane of the ecliptic. Adding 235 to 1639, we have 1874; there was no transit 235 years from 1631, as Venus was then too far past the ascending node at the time of its inferior conjunction; but there will be a transit at that node in 1882. These transits take place in December (744, 745). The transits of 1761 and 1769 took place at the descending node, and so will those of 2004 and 2012, the first of which comes 235 years after 1769, not 1761, the transit of 1761 failing to be repeated. The transits at the descending node happen in June.

754. Examples of cycles like these might be made very numerous; in fact, all periodical events happen in cycles of greater or less exactness.

755. The Romans, like the Greeks, wished to make their civil years conform to the tropical year, and yet to reckon time with regard to lunations. Their calendar, of course, fell into confusion, the years being lengthened by the insertion of a number of days decided upon each year by the priests, with regard, it is said, rather to politics than to science. Julius Cæsar put an end to this disorder by employing the astronomer Sosigenes to reform the calendar (302). As the exact length of the tropical year was still unknown, it was decided that the civil year should ordinarily consist of 365 days, and that an additional day should be inserted every fourth year. The period called a Julian year is accordingly $365\frac{1}{4}$ days of mean time. The Julian period is a period of 7,980 Julian years, assumed to begin in the year 4713 B.C.; it is of some use in the study of chronology, but not for any ordinary purpose.

756. In the course of the sixteen centuries following the time of Cæsar, it became obvious that the time occupied by four tropical years was somewhat less than the 1,461 days which make up four Julian years. Our present calendar was contrived, according to the direction of Pope Gregory XIII., to keep the vernal equinox as nearly as might be to the 21st of

March, on which it occurred at the time of the important ecclesiastical council held at Nice (or Nicæa) in Asia Minor, in the year A.D. 325. This council had made rules for the time at which the church festival of Easter should be yearly celebrated; and the rules thus made took it for granted that the vernal equinox happened on March 21st. In the time of Gregory XIII., the day on which the vernal equinox happened was March 11th, according to the Julian calendar. The reformation of the calendar was accomplished by omitting ten days, the day after the 4th of October, 1582, being called the 15th of October; and to prevent the need of like changes in after times, it was determined that the years 1700, 1800, and 1900, should have only 365 days, instead of 366, as they would have had under the old rule. The year 2000, however, will have 366 days, according to the Gregorian calendar; the years 2100, 2200, and 2300, 365 days each; 2400 will have 366, and so on.

757. The Catholic nations of Europe immediately adopted the change made in the calendar by the Pope; but other nations continued for a time, as the Russians do still, to use the Julian calendar. In England, the change from the Old Style to the New Style, as it was called, took place in 1752. As the year 1700 had 366 days, according to the Old Style, eleven days had to be omitted to make the calendar agree with that of Catholic nations. For legal purposes, the English year, according to the Old Style, had been considered to begin on March 25th, the date of the church festival of the Annunciation. The introduction of the New Style, by statute, set the beginning of the legal year at January 1. The legal year 1751, in England, lasted only from March 25th to the end of December.

758. The length and the name of each of our months have come down to us from the Romans, who made no permanent change in either after the time of Julius Cæsar and his successor Augustus. The week was not used as a measure of time by the early Greeks and Romans, although it was in use in ancient times among various Eastern nations.

The English names of the days of the week are mainly derived from the old Teutonic mythology. But these matters form, properly speaking, no part of the history of astronomy.

759. We may say much the same of the numerous speculations made with respect to the distant past and remote future of the universe. Most of them can be made as well without any knowledge of astronomical subjects as with it, and, in fact, they are seldom made by professional astronomers.

760. It is usual, however, to consider what is called the nebular hypothesis as a part of the science of astronomy. This hypothesis was suggested by the German philosopher Kant, and also by the French mathematician Laplace, who has been named above as one of the most distinguished inquirers into the nature of planetary movements. The reason for regarding the nebular hypothesis as important is that it enables us to account on mathematical principles for certain facts observed in the Solar System, and directs our attention to the systematic observation of other facts; while most speculations on the early condition of the universe offer no opening for exact reasoning or the strict application of known laws, but are invented merely to account for what now exists by vague suggestions relating to matters which are at present wholly beyond the reach of observation and exact calculation.

761. According to the nebular hypothesis, the matter now composing the various objects which make up the Solar System was once in the form of a nebulous mass, having a movement of rotation. The temperature of this nebula was high enough to keep it in the gaseous state: but it gradually cooled and shrunk together, while the speed of its rotation increased according to known laws. Its outer portions were separated from the rest by the inertia they acquired by this increasingly rapid rotation; and this process was repeated a number of times. Each time it was repeated, a ring of matter was formed around the nebula; and the matter of each

ring was ultimately either collected into a single planet, or into a group of bodies differing more or less in size.

762. If any one wishes really to comprehend this hypothesis, he must take much more trouble and study much harder than most people either can or will. On the other hand, no sound opinion can be formed about a theory which is not thoroughly understood. It is not surprising, therefore, that the opinions put forward about the nebular hypothesis are often worthless. The opinions of most men who know enough to discuss the hypothesis with profit seem at present to be in favor of its truth.

763. There are certain facts which any one can see to be favorable to the nebular hypothesis. The existence of large gaseous bodies seems to have been proved by the spectroscope; it was formerly doubted. Modern geologists seem decidedly to think that the Earth sends out more heat than it receives from the Sun, stars, meteors (249), or any other sources. The ring of Saturn, whether it is or is not made up of small satellites, presents us with a case of the actual formation by some means of an object most easily accounted for by the repetition on a smaller scale of the process by which Saturn itself was formed.

764. But it is still too early for most of us to regard the nebular hypothesis as more than a useful supposition, which tends to direct our observation to the actual condition of the Earth, as well as to that of the Sun and of the nebulæ, so far as their condition can be observed.

765. The ordinary supposition with regard to the future of the Solar System is that the various bodies of which it consists will continue to cool for an indefinitely long time, while the resistance of the ether or of other matter through which they may be moving will gradually bring all the planets to the Sun. Hence the Solar System would finally come to consist of the Sun alone, deprived of its light and heat, and destined in the lapse of ages to become part of some larger body by a continuation of the process which had put an end to the separate planets.

766. Another speculation regards the fall of the planets into the Sun as sufficient to produce heat enough to restore these bodies to their former nebulous condition. But according to modern views regarding what is called the dissipation of energy, the final result of all changes would be to extinguish motion, and uniformly diffuse heat, throughout the universe.

767. It is to be observed, however, that under the actual limitations of human knowledge we are brought in the consideration of all questions like those just mentioned to the subject of infinity. We cannot regard time otherwise than as infinite, because we have no experience of any cessation of time. On the other hand, we can regard all events as coming to a stand, because particular events are observed to do so. Water thrown on the roof of a house runs off upon the ground; but if it falls into a hollow metal basin, it settles into the lowest part of the basin and comes to rest. So, too, a hot iron gradually comes to the temperature of the air around it, and ceases to cool.

768. But if we regard time as a quantity, we see that it is constantly lost and never replaced. If we did not take it for granted that there is an infinite amount of time to draw upon, we should suppose that time must some day be all used up. The course of events, then, when regarded as time, seems endless or not as we please. So, too, when we regard it on mechanical principles, we find it tending to a close, unless we please to regard it as endless; or, in other words, unless we regard the stock of available energy in the universe as infinite. We soon come, both in the case of time and in that of energy, to the limit of human knowledge, which we call infinity.

769. We cannot, then, accept any speculations with regard to the distant future as forming part of science. Besides encountering the impossibility of learning any thing which is infinite, we are obliged in these speculations to extend the application of what we call the laws of nature to objects so remote in space and time that we have little security in predicting any thing with respect to them.

770. That every thing we can observe is in a state of change is perhaps the most general law which we can form at present; and we may reasonably think, whatever guesses we make about the past and future of the Solar System, that the Earth was not always, and is not always to be, a suitable dwelling-place for mankind, or for any creatures nearly resembling mankind. But even this is an idle speculation. God's ways are not our ways, nor are his thoughts our thoughts. The laws of nature, to which our thoughts are confined, are necessarily mere fragments of the great order of nature which exists, as we hope, by the authority of an infinite Creator, to whose wisdom and goodness we may trust. All our sciences consist in the study of such parts of God's works as are within the reach of our faculties now, not in conjectures carried so far beyond the bounds of our knowledge that they fail to point out to us what we should next observe.

# CHAPTER XVI.

## NOTES, REFERENCES, AND STATISTICS.

771. THE following abbreviations of the titles of works will be employed in this chapter. In the references to be given, Arabic numerals will denote the page referred to (with the exceptions named below), and Roman numerals the volume.

A. American Ephemeris and Nautical Almanac for 1877.

C. Comptes Rendus Hebdomadaires de l'Académie des Sciences (Paris).

D. Astronomical Observations and Researches made at Dunsink, the Observatory of Trinity College, Dublin. Second Part. Dublin, 1873.

G. Hypsometrical Tables, in the "Tables, Meteorological and Physical, prepared for the Smithsonian Institution by Arnold Guyot. Second edition. Washington, 1858."

H. Papers by W. Herschel, read before the Royal Society of London (referred to by the years in which they were read).

J. American Journal of Science and Arts (referred to by the year, volume, and page).

L. Annalen der Sternwarte in Leiden, Band III. Haag, 1872.

M. Memoirs of the Royal Astronomical Society, London.

Mn. Monthly Notices of ditto.

N. Astronomische Nachrichten (referred to, as usual, only by the number of that periodical containing the article cited).

O. Outlines of Astronomy, by Sir John F. W. Herschel. Fifth edition. London, 1858.

P. Annales de l'Observatoire Impérial de Paris. Mémoires.

S. Die Sonne, von P A. Secchi Autorisirte Deutsche Ausgabe und Originalwerk, herausgegeben durch Dr. H. Schellen. Braunschweig, 1872.

W. Appendix II. to the "Astronomical and Meteorological Observations made at the United States Naval Observatory during the year 1865."

Z. Ueber die Natur der Cometen. Von Johann Carl Friedrich Zöllner. Leipzig, 1872.

772. **Dimensions of the Earth.** On the assumption that the Earth is a geometrical oblate spheroid of revolution, its equatorial and polar semidiameters were determined by Bessel as follows (N. 438): —

| | |
|---|---|
| Equatorial semidiameter . . . | 3,272,077.14 toises. |
| Polar ,, . . . | 3,261,139 33 ,, |

Ratio of the difference between these numbers to the first $\frac{1}{299.1528}$; to the second $\frac{1}{298.1528}$.

These results were derived from computations founded on the measurements, at different times and in different parts of the Earth, of ten arcs of meridians. The value of 1 toise in English fathoms was taken by Bessel (N. 333) to be 1.06576542; hence 1 toise contains 6.39459252 English feet. Others reckon (G. 115) 1 toise to be equivalent to 6.394590 English feet or 6.394219 American feet. With these last values, we find from Bessel's results:

| | | | | | | |
|---|---|---|---|---|---|---|
| Equatorial diameter of the Earth | | | | | 41.847,184 | English feet. |
| ,, | ,, | ,, | ,, | ,, | 41,844,756 | American ,, |
| ,, | ,, | ,, | ,, | ,, | 7.925.14 | ,, miles. |
| Polar | ,, | ,, | ,, | ,, | 41,707,298 | English feet. |
| ,, | ,, | ,, | ,, | ,, | 41,704,878 | American ,, |
| ,, | ,, | ,, | ,, | ,, | 7,898.65 | ,, miles. |

The following results were obtained by Clarke from data partly the same as Bessel's; see p. 773 of the Account of the Principal Triangulation in the Ordnance Survey of Great Britain and Ireland. London, 1858.

Regarding the section along the Earth's axis as not necessarily elliptical in shape:

| | | |
|---|---|---|
| Equatorial semidiameter | 20,927,197 | English feet. |
| Polar ,, | 20,855,493 | ,, ,, |

Half ratio of sum to difference of these numbers 291.36.

Regarding the section as elliptical:

| | | |
|---|---|---|
| Equatorial semidiameter | 20,926,348 | English feet. |
| Polar ,, | 20,855,233 | ,, ,, |

Half ratio of sum to difference of these numbers 293.76.

Another determination by Clarke is as follows (M. xxix. 39): the assumption in this case being that the Earth is an ellipsoid, but not an ellipsoid of revolution, so that its equator is an ellipse. There is some ground for this assumption, but further surveys are required to determine the shape of the equator with certainty (M. xxix. 42).

| | | |
|---|---|---|
| Longest equatorial semidiameter, in longitude 13° 58′.5 east from Greenwich . . . . . | 20,926,485 | English feet. |
| Shortest equatorial semidiameter, in longitude 103° 58′.5 east from Greenwich . . . . . | 20,921,177 | ,, ,, |
| Polar semidiameter . . . . . | 20,853,768 | ,, ,, |

Fergola, in a treatise on the relative positions of the Earth's axes of rotation and of figure, published at Naples in 1874, finds from the surveys hitherto made that, supposing the Earth to have the form of an oblate ellipsoid of revolution, its axis of rotation is inclined 1° 8′.4 to its shortest axis, and that, if we reckon longitude by meridian planes passing through the shortest axis, the north pole of rotation is 239° 31′.5 east of Greenwich.

773. **Latitudes and Longitudes of Observatories.** In the following table, the sign + before a latitude signifies north and — south; before a longitude + signifies west of the United States Naval Observatory at Washington, and — east of it (A. 475, 476).

| Place. | Latitude. | | | Longitude. | | |
|---|---|---|---|---|---|---|
| | ° | ′ | ″ | H. | M. | S. |
| Berlin, Prussia | +52 | 30 | 16.7 | −6 | 1 | 47.50 |
| Cambridge, Massachusetts | +42 | 22 | 48.1 | −0 | 23 | 41.11 |
| Cape of Good Hope, Africa | −33 | 56 | 3.2 | −6 | 22 | 7.82 |
| Chicago, Illinois | +41 | 50 | 1.0 | +0 | 42 | 14.69 |
| Greenwich, England | +51 | 28 | 38.2 | −5 | 8 | 12.12 |
| Madras, India | +13 | 4 | 9.2 | −10 | 29 | 9.40 |
| New York, N. Y. | +40 | 43 | 48.5 | −0 | 12 | 15.47 |
| Paramatta (near Sydney), New South Wales | −33 | 48 | 49.8 | −15 | 12 | 18.37 |
| Paris, France | +48 | 50 | 11.0 | −5 | 17 | 33.22 |
| Santiago, Chili | −33 | 26 | 42.0 | −0 | 25 | 21.73 |
| Washington, D. C. | +38 | 53 | 38.8 | 0 | 00 | 00.00 |

Latitude of Telegraph Hill, San Francisco, California, +37° 48′ 6″.1 by note on a chart in United States Coast Survey Report for 1852. Longitude of a Coast Survey station at San Francisco, in 1869, $3^h\ 25^m\ 7^s.33$ west of Cambridge Observatory (J. 1872, III. 398).

These data may aid in the approximate determination of other latitudes and longitudes by means of maps.

774. **Refraction and Dip**, according to the tables in Chauvenet's Spherical and Practical Astronomy. Mean refraction, at 10° zenith distance, 0′ 10″.3; at 45° zenith distance, 0′ 58″.2; at 80° zenith distance, 5′ 19″.2; at 90° zenith distance, 36′ 29″. These examples illustrate the rapidity with which refraction increases, near the horizon, with the increase of zenith distance.

Dip of the sea horizon, when the eye is 5 feet above the sea level, 2′ 11″; at a height of 10 feet, 3′ 6″; at a height of 100 feet, 9′ 48″.

775. **Rotation of the Sun.** In studying the rotation of the Sun, the values of the following quantities are investigated: —

The period of rotation, expressed in days of mean time, which we may denote by T; or the angle through which the Sun turns in one day of mean time, denoted by $\xi$.

The heliocentric longitude of the ascending node of the Sun's equator, denoted by $\Omega$.

The angle between the planes of the ecliptic and of the Sun's equator, denoted by $i$.

Recent attempts to determine these quantities have led to the following results. The dates (called epochs) to which the determinations are meant to apply are always given in work of this kind, since no determination can be true except for some particular time, owing to the continual shifting of the vernal equinox and other points with reference to which our computations are made. But in the case now before us, the disagreements between results obtained within a few years of each other are much greater than the amounts, during the intervals between the epochs of these results, of the changes due to the cause just named.

Laugier found (C. xv. 941) for the beginning of 1840, $T = 25.34$ $\Omega = 75° 8'$ $i = 7° 9'$.

Spörer (N. 1615) found from his early observations, $T = 25.1833$ $\Omega = 74° 11' 6''$ $i = 6° 54' 43''$; and from a later set, $T = 25.2590$ $\Omega = 74° 47' 46''$ $i = 6° 58' 5''$; combining these results with regard to the number of observations on which each depends, he concluded, for the middle of 1866, $T = 25.234$ $\Omega = 74° 36'$ $i = 6° 57'$.

Carrington (Observations of the Spots on the Sun, London, 1863) found for the beginning of 1850, $\Omega = 73° 40'$ $i = 7° 15'$. He represented the varying time of rotation indicated by spots at different distances from the Sun's equator by means of two empirical formulæ, either of which would represent his observations tolerably well. These formulæ are —

$$\xi = 865' \mp 165' \sin^{\frac{7}{4}} l \qquad \xi = 865' \mp 165' \sin^{\frac{7}{4}} (l - 1°)$$

in which $l$ stands for the arc of a meridian of the Sun extending from the Sun's equator to that point for which $\xi$ is required. Similar formulæ have been drawn up by other astronomers. Faye's (C. lx. 147) is $\xi = 862' - 186' \sin^2 l$; Spörer's (N. 1542) is $\xi = 16°.8475 - 3°.3812 \sin (l + 41° 13')$; and Zöllner's (N. 1850) is $\xi = \frac{863'.8 - 613'.2 \sin^2 l}{\cos l}$ for the Sun's northern hemisphere, $\xi = \frac{861'.8 - 620'.5 \sin^2 l}{\cos l}$ or $\xi = \frac{863'.8 - 623'.1 \sin^2 l}{\cos l}$ for the Sun's southern hemisphere.

776. **Parallax of the Sun.** The mean equatorial horizontal parallax of the Sun (or the equatorial horizontal parallax

of the Sun at a time when its distance from the Earth is equal to the semiaxis major of the Earth's orbit) is given by recent authorities as follows : —

Stone, from observations of Mars in 1862 (M. xxxiii. 97), 8″.94.

Stone, from the observations of the transit of Venus in 1769 (Mn. xxviii. 265), 8″.91.

Newcomb, by the combination of the results obtained by a number of methods (W. p. 29), 8″.85.

Cornu, from his experiments on the velocity of light (C. lxxvi. 341), 8″.86.

From these data it appears that the Sun's parallax is probably known to 0″.1, but probably not known within 0″.05.

777. **Distance of the Sun.** The trigonometrical tangent of the Sun's parallax is equal to the quotient which would be obtained by dividing the equatorial semidiameter of the Earth by the semiaxis major of the Earth's orbit.

The tangent of 8″.00 is 0.000038785 nearly.
" " " 8″.85 " 0.000042906 "
" " " 8″.90 " 0.000043148 "
" " " 9″.00 " 0.000043633 "

The tangents of these small angles are nearly the same as the sines of the same angles, or as the ratios of the arcs of the same angles to the radius of any circle to which those arcs belong. They therefore increase uniformly with the angles, at the rate of 0.000004848 for every second. Upon calculating the semiaxis major of the Earth's orbit (or the mean distance of the Sun), by means of the data given above, it will be found that a change of 0″.05 in the parallax employed makes a difference of over half a million miles in the result. It is useless, therefore, to attempt at present to state the Sun's distance in smaller units than millions of miles; and since all measurements of distances greater than that between the Sun and the Earth are based upon this fundamental distance, we see that none of these measurements can be stated in smaller units than millions of miles. The mean distance of the Sun, by the above data, is accordingly ninety-two millions of miles.

778. **Dimensions of the Sun.** The mean apparent semi-diameter of the Sun is 16′ 2″ (A., Appendix, 4). Twice the product of the tangent of this angle (0.0046639) by the Sun's mean distance gives us the Sun's diameter, which is reduced nearly five thousand miles by an increase of 0″.05 in the parallax employed. It follows that we may be content for the present to state the Sun's diameter in round numbers at 860,000 miles.

779. **Mass of the Sun.** A formula for the number of times that the Sun's mass contains the Earth's is given by Newcomb (W. p. 27) as follows: $\log M\pi^3 = 8.35488$; in which M stands for the required quantity, and $\pi$ for the Sun's parallax. An increase of 0″.05 in the parallax employed will diminish the result by about 6,000; we can conclude only that the Sun's mass is from 320,000 to 330,000 times as great as the Earth's. The value of the Earth's mass given below, in the list of the masses of the planets, depends upon older determinations of parallax than those already quoted.

780. **Periods and Nature of Solar Spots.** The periodicity of solar spots was discovered by Schwabe. Wolf has been the principal inquirer into the length of their periods. See numerous papers in the Astronomische Nachrichten, especially N. 839, 1043, 1160, 1185, 1199, 1223, 1294, 1420, 1540, 1577, 1862. For theories of the constitution of the Sun and of its spots at variance with that mentioned in the text, see papers by Spörer and by Zöllner in the Astronomische Nachrichten, especially N. 1542, 1556, 1612, 1835, 1849, 1969, 1974.

781. **Solar Heat.** On the subject of the heat of the photosphere different astronomers hold very different opinions, some of which may be learned in the following works. (S. 198–211, 566–584. C. lx. 144. J. 1873, vi. 153. N. 1815.)

782. **Number of Stars.** The number of stars visible to the naked eye in Germany, according to Heis (Neuer Himmels-Atlas, Sternverzeichniss, p. xiii.), is 5.421; adding a proportionate number for the part of the sky not seen from Germany, the result is 6,800 for the whole sky. But Gould

estimates that 15,000 could be seen if the sky was everywhere as clear as it is at Cordoba, in the Argentine Republic. See p. 19 of his Address on the occasion of his reception at Boston, June 22, 1874.

783. **Variable Stars Algol and Mira.** According to Schönfeld (N. 1906) the period of Algol is 2 days 20 hours 48 minutes 53.777 seconds (or about 2.867 days) of mean time. When we attempt to determine it correctly within a minute, we must take account of the variation of the distance of the star which is due to the Earth's motion in its orbit, since light requires time to reach us. The following predictions by Schönfeld (N. 2001) of the minima of Algol are in Paris astronomical mean time, and will enable the reader to calculate, for some years to come, the times at which the star will appear faint. The difference of longitude between Paris (773) and the place for which the calculation is made must of course be taken into account. The predictions have been selected so that their times may answer to the evening hours of the United States.

1874, Dec. 2, $13^h\ 14^m$ (in civil time, Dec. 3, $1^h\ 14^m$ A.M.); Dec. 22, $14^h\ 58^m$; 1875, Jan. 14, $13^h\ 31^m$; Feb. 3, $15^h\ 16^m$; Feb. 26, $13^h\ 50^m$; March 18, $15^h\ 35^m$; April 10, $14^h\ 8^m$; Aug. 17, $14^h\ 42^m$; Sept. 9, $13^h\ 11^m$; Sept. 29, $14^h\ 51^m$; Oct. 22, $13^h\ 20^m$; Nov. 11, $15^h\ 2^m$; Dec. 4, $13^h\ 33^m$; Dec. 24, $15^h\ 17^m$.

A minimum of Mira, according to Schmidt (N. 1988), occurred Jan. 6, 1874.

784. **Places of Stars.** The following table contains the mean right ascensions and declinations, for the beginnings of 1850 and of 1875, of the principal stars named in this work. The places of Mira and Algol for 1850 are taken from the Catalogue of the British Association, and for 1875 from the Vierteljahrsschrift der Astronomischen Gesellschaft. The places of the other stars are taken from the English Nautical Almanacs for 1850 and for 1875, in the first of which north and south declinations are marked respectively N. and S., in the second + and —.

| Names. | Right ascensions 1850. | | | Declinations 1850. | | | Right ascensions 1875. | | | Declinations 1875. | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | H. | M. | S. | ° | ′ | ″ | H. | M. | S. | ° | ′ | ″ |
| Polaris (α Ursæ Minoris) | 1 | 5 | 0.817 | N. 88 | 30 | 35.28 | 1 | 12 | 59.063 | + 88 | 38 | 33.82 |
| Achernar (α Eridani) | 1 | 32 | 7.302 | S. 58 | 0 | 0.17 | 1 | 33 | 3 199 | − 57 | 52 | 19.43 |
| Mira (ο Ceti) | 2 | 11 | 46 53 | S. 3 | 39 | 41.8 | 2 | 13 | 1.927 | − 3 | 32 | 46.90 |
| Algol (β Persei) | 2 | 58 | 25.55 | N. 40 | 22 | 25.4 | 3 | 0 | 2.433 | + 40 | 28 | 20 38 |
| Aldebaran (α Tauri) | 4 | 27 | 19 075 | N. 16 | 12 | 11.26 | 4 | 28 | 44 952 | + 16 | 15 | 21.60 |
| Capella (α Aurigæ) | 5 | 5 | 36 915 | N. 45 | 50 | 20.49 | 5 | 7 | 27.437 | + 45 | 52 | 5.22 |
| Rigel (β Orionis) | 5 | 7 | 19.809 | S. 8 | 22 | 45.51 | 5 | 8 | 31.826 | − 8 | 20 | 52.74 |
| Betelgeux (α Orionis) | 5 | 47 | 3.107 | N. 7 | 22 | 26.87 | 5 | 48 | 24.280 | + 7 | 22 | 53.74 |
| Canopus (α Argus) | 6 | 20 | 37.480 | S 52 | 36 | 55 63 | 6 | 21 | 10.734 | − 52 | 37 | 41.28 |
| Sirius (α Canis Majoris) | 6 | 38 | 32.336 | S. 16 | 30 | 52 65 | 6 | 39 | 38.350 | − 16 | 32 | 46.16 |
| Castor (α Geminorum) | 7 | 25 | 1.283 | N. 32 | 12 | 42 80 | 7 | 26 | 37 353 | + 32 | 9 | 37.77 |
| Procyon (α Canis Minoris) | 7 | 31 | 26 733 | N. 5 | 36 | 19.22 | 7 | 32 | 45.499 | + 5 | 32 | 36.01 |
| Pollux (β Geminorum) | 7 | 36 | 7.796 | N. 28 | 23 | 1.08 | 7 | 37 | 39.885 | + 28 | 19 | 34.09 |
| Regulus (α Leonis) | 10 | 0 | 22.706 | N. 12 | 41 | 53.32 | 10 | 1 | 42.798 | + 12 | 34 | 38.18 |
| Variable star in Argo (η Argus) | 10 | 39 | 15.219 | S. 58 | 53 | 47 87 | 10 | 40 | 12.909 | − 59 | 1 | 36.53 |
| Bright star in the Cross (α Crucis) | 12 | 18 | 17.540 | S. 62 | 15 | 59.44 | 12 | 19 | 39.033 | − 62 | 24 | 17.82 |
| Spica (α Virginis) | 13 | 17 | 17.734 | S. 10 | 22 | 36.61 | 13 | 18 | 36.516 | − 10 | 30 | 29.57 |
| Bright star in the Centaur (β Centauri) | 13 | 53 | 17.196 | S. 59 | 38 | 45.69 | 13 | 55 | 1.074 | − 59 | 46 | 7.89 |
| Arcturus (α Bootis) | 14 | 8 | 49.201 | N. 19 | 57 | 56.09 | 14 | 9 | 57.630 | + 19 | 50 | 3.67 |
| Bright star in the Centaur (α Centauri) | 14 | 29 | 27.775 | S. 60 | 12 | 37.85 | 14 | 31 | 8.518 | − 60 | 18 | 54.20 |
| Antares (α Scorpii) | 16 | 20 | 13.024 | S. 26 | 5 | 38.61 | 16 | 21 | 44.709 | − 26 | 9 | 9.05 |
| Vega (α Lyræ) | 18 | 31 | 51.519 | N. 38 | 38 | 49.26 | 18 | 32 | 42.372 | + 38 | 40 | 5.95 |
| Altair (α Aquilæ) | 19 | 43 | 27.787 | N. 8 | 28 | 33.69 | 19 | 44 | 41.043 | + 8 | 32 | 22.64 |
| Arided (α Cygni) | 20 | 36 | 19.069 | N. 44 | 44 | 47.66 | 20 | 37 | 10.220 | + 44 | 50 | 4.04 |
| Fomalhaut (α Piscis Australis) | 22 | 49 | 20.978 | S. 30 | 24 | 56.08 | 22 | 50 | 44.303 | − 30 | 17 | 3.99 |

785. **Data relating to the Places of Stars.** The yearly amount of precession for 1800 is 50″.2411 ; and it is now yearly increasing by 0″.0002268. Hence for 1850 it is 50″.2524 ; for 1875, 50″.2581. The mean obliquity of the ecliptic for 1877 (or its obliquity when we disregard the effect of nutation) is 23° 27′ 18″.46 ; it diminishes at present by 0″.1272 in 100 days ; hence for 1875 it is 23° 27′ 19″.39. The constant of aberration (or half the greatest difference, due to aberration, between two of the apparent places of any star) is 20″.4451. (A. 248 ; Appendix, 3.)

The change in the right ascension and declination of a star occasioned by precession vary according to its place as well as with time. For 1877, the yearly changes are as follows : $a$ standing for right ascension and $\delta$ for declination. The increase in $a$ is $3^s.07229 + 1^s.33693 \sin a \tan \delta$ ; that in $\delta$ is $20''.0540 \cos a$ (A. 258). The angles having at the beginning of 1877 the values $1^s.33693$ and $20''.0540$ are equal (405). Their decrease in ten years is at present $0^s.00006$ or $0''.0009$. The angle having at the beginning of 1877 the value $3^s.07229$ is now increasing at the rate of $0^s.00020$ in ten years. The student who has any knowledge of trigonometry will perceive that the right ascensions of most, but not of all, stars increase by the effect of precession ; while if we consider a northward movement as an increase of declination, precession increases declination in half the celestial sphere and lessens it in the other half. With the data already given, we may calculate the precession in $a$ and $\delta$ of any star in our list for any time not very remote. For example, let us calculate the effect of precession on the star Arcturus from 1850 to 1875. As its $a$ and $\delta$ are constantly changing, and yet are required in the calculation, it will be best to take them half-way between 1850 and 1875. We can do this at once by means of the list ; if we had the star's place given for some one date only, we might begin by using that place in a rough calculation of its place for $1862\frac{1}{2}$ (or the middle of 1862). We have from the list, for $1862\frac{1}{2}$, $a = 14^h\ 9^m\ 23^s$, or 212° 21′, which is sufficiently accurate for our purpose ; $\delta = + 19°\ 54'$. The yearly

increase of $a$, for $1862\frac{1}{2}$, appears from the data given above to be $3^s.072 + 1^s.337 \sin a \tan \delta$, and the yearly increase of $\delta$ to be $20''.055 \cos a$. The computation will accordingly be as follows: —

| | | | |
|---|---|---|---|
| log 1.337 . . . | 0.12613 | log 20.055 . . | 1.30222 |
| log sin 212° 21′ | 9.72843 | log cos 212° 21′ | 9.92675 |
| log tan 19° 54′ . | 9.55870 | | |
| | 9.41326 | | 1.22897 |

By the rules of trigonometry, the numbers corresponding to the logarithms just obtained are both negative. The right ascension of Arcturus was therefore yearly increasing, at the time $1862\frac{1}{2}$, by $3^s.072 - 0^s.259$, or $2^s.813$; its declination, at the same time, was yearly diminishing by $16''.94$. Hence, between 1850 and 1875, its right ascension increased about $70^s.325$ and its declination diminished about $423''.50$. If Arcturus had no proper motion, these differences would nearly answer to the change in its mean place (562) between 1850 and 1875. The actual differences, from the list, are $68^s.429$ and $472''.42$; we find, then, that during twenty-five years the star's proper motion diminished its right ascension (or made it retrograde) about $1^s.9$, and carried it southwards nearly $49''$. This is a large proper motion compared with that of most stars. During the last two thousand years, Arcturus must have changed its apparent place among the other stars more than a degree.

786. **Examples of Binary Stars and of Stellar Parallax.** The places of the stars named in this section have been given above, except those of $\zeta$ Herculis, $\xi$ Ursæ Majoris, and 61 Cygni, the approximate places of which for 1875 are respectively $16^h\ 36^m\ 35^s, + 31°\ 50'$; $11^h\ 11^m\ 31^s, + 32°\ 14$; $21^h\ 1^m\ 18^s, + 38°\ 8'$. When two or three periods of revolution are given for a binary star, they show how nearly the results of different inquirers agree. A parallax of $1''$ answers to a distance from us of 206,265 times the semiaxis major of the Earth's orbit; and as the angles of parallax are so small that their arcs may be taken for their tangents, the distances of two stars are inversely as their parallaxes.

| Name. | Period in years. | Parallax. | Authorities referred to. |
|---|---|---|---|
| ζ Herculis . . | 30.216, 34.57, 36.357 | . . . . . | O. 615; Mn. xxxiv. 426. |
| ξ Ursæ Majoris | 58.262, 60.60, 61.576 | . . . . . | O. 615; Mn. xxxiv. 426. |
| α Centauri . . | 77.00, 81.40 | 0″.9 to 1″.0 | O. 593, 615; M. xii. 370, xx. 98; Mn. iv. 169. |
| α Geminorum . | 252.66, 632.27 | . . . . . | O. 615. |
| 61 Cygni . . | Over 500 { No orbit; only a difference of proper motion. } | Under 0″.4 | O. 593, 619; N. Ergänzungs-Heft; M. xxxii. 95. |
| Sirius . . . | 49.418 | About 0″.2 | O. 593; Mn. v. 6; Mn xxv. 39. |
| Vega . . . . | . . . . . | About 0″.2 | D. 57. |

787. **Elements of Planets and Satellites.** A full statement of a planet's movement about the Sun, or that of a satellite about its planet, includes —

I. The number of days of mean time in which the moving body makes one sidereal revolution; or, which will serve a like purpose, a number of seconds of arc, the product of which by that number of days is 1,296.000 (the number of seconds in the whole circle). This is called the mean motion of the moving body, or its mean daily motion, and is often denoted by $\mu$. Sometimes the mean yearly motion of the moving body is used as one of its elements. This mean yearly motion is to the mean daily motion as one Julian year of 365¼ days is to one day. It is often denoted by $n$.

II. The ratio of the semiaxis major of the planet's orbit to that of the Earth's orbit. This is usually denoted by $a$.

III. The ratio of the mass of the planet to that of the Sun. This is denoted by $m$.

IV. The eccentricity of the planet's orbit. This is denoted by $e$, or by $\varepsilon$.

V. The heliocentric longitude of the planet's perihelion, denoted by $\pi$.

VI. The heliocentric longitude of the ascending node of the orbit, often denoted by $\Omega$, sometimes by $\theta$.

VII. The inclination of the plane of the orbit to the plane of the ecliptic, denoted by $i$, $\iota$, or $\phi$; the symbol $\phi$ is frequently used in a different sense, to denote the angle, the sine of which is $e$.

VIII. The date (usually called the epoch) for which elements IV., V., VI., and VII., have been calculated.

IX. The mean anomaly, denoted by M, of the planet itself at this epoch: or an angle equal to the sum of M and $\pi$, and called the planet's mean longitude. This angle is denoted by L, $l$, or sometimes $\varepsilon$.

These nine data are not always enumerated in the same order, and may be reduced to seven by omitting the mass (which is necessary in the case of an asteroid or comet), and taking the epoch at the time of the planet's perihelion passage; this is customary in calculations of the orbits of comets, and makes the element L or M superfluous. If a comet is supposed to move in a parabola, the element $e$ becomes equal to unity, and disappears from the list of elements. The orbit is then easier to compute; and for this reason a comet is always supposed to move in a parabola, if a parabolic orbit will satisfy the observations. Since $a$ is infinite in a parabolic orbit, it is replaced by $q$, the distance from focus to perihelion, in terms of the semiaxis major of the Earth's orbit.

788. **Approximate elements of the eight principal planets**, by Le Verrier (P. ii. 58 to 62) are given on the following page. The epoch is mean noon, Jan. 1, 1850, with the mean equinox and ecliptic of that date.

789. **Corrections to these Elements.** Le Verrier found that the elements of the Earth adopted at the outset of his investigations, and here quoted, required the following corrections (P. iv. 52, 53, 97 to 104): $\pi$ should be diminished by $18''.5$; $l$ increased by $7''.39$; $e$ increased by 0.00000058; and the mean yearly motion, $n$ (derived from the time of the sidereal revolution), increased by $0''.0603$. The solar parallax previously accepted ($8''.57$), and the received mass of the Earth, were shown by this investigation to be too

| Name. | Period in days. | $m$ | $a$ | $e$ |
|---|---|---|---|---|
| Mercury . . | 87.9692580 | $\frac{1}{3,000,000}$ | 0.3870987 | 0.2056179 |
| Venus . . | 224 7007869 | $\frac{1}{401,847}$ | 0.7233322 | 0.0068334 |
| Earth . . . | 365.2563744 | $\frac{1}{354,936}$ | 1.0000000 | 0.01677046 |
| Mars . . . | 686.9796458 | $\frac{1}{2,680,337}$ | 1.523691 | 0.0932616 |
| Jupiter . . | 4,332.5848212 | $\frac{1}{1,050}$ | 5.202798 | 0.0482383 |
| Saturn . . | 10,759.2198174 | $\frac{1}{3,512}$ | 9.538852 | 0.0559956 |
| Uranus . . | 30,686.8208296 | $\frac{1}{24,000}$ | 19.182639 | 0.0465775 |
| Neptune . . | 60,126.72 | $\frac{1}{14,400}$ | 30.03697 | 0.0087195 |

| Name. | $\pi$ | $\phi$ | $\theta$ | $l$ |
|---|---|---|---|---|
| | ° ′ ″ | ° ′ ″ | ° ′ ″ | ° ′ ″ |
| Mercury . . | 75 7 0.0 | 7 0 8.16 | 46 33 3.25 | 327 15 19.9 |
| Venus . . | 129 23 56.0 | 3 23 30 75 | 75 19 4.15 | 245 33 14.4 |
| Earth . . . | 100 21 40.0 | . . . . . | . . . . . | 100 46 36.1 |
| Mars . . . | 333 17 50.5 | 1 51 5.08 | 48 22 44.75 | 83 40 50.6 |
| Jupiter . . | 11 54 53.1 | 1 18 40.31 | 98 54 20.45 | 160 1 20.3 |
| Saturn . . | 90 6 12.0 | 2 29 28.14 | 112 21 43.96 | 14 50 40.6 |
| Uranus . . | 168 16 45.0 | 0 46 29.91 | 73 14 14.35 | 28 26 41.5 |
| Neptune . . | 47 14 37.3 | 1 46 58.97 | 130 6 51.58 | 335 8 58.5 |

small, unless a group of asteroids was supposed to exist near the orbit of the Earth (P. vi. 187).

Le Verrier's corrections to the elements of Mercury are as follows (P. v. 107): $\pi$ should be increased by 13″.93; $l$ by 0″.53; $\theta$ by 5″.50; $e$ diminished by 0.00001312; $\phi$ by 0″.45. The corrected mass of Mercury is $\frac{1}{5,310,000}$ of the Sun's (P. vi. 92).

The corrections to the elements of Venus are as follows (P. vi. 95): $\pi$ should be increased by 3′ 18″.5; $l$ by 0″.30; $\theta$ by 48″.15; $\phi$ by 4″.08; $e$ by 0.00000991; $m$ reduced to $\frac{1}{412,150}$ (P. vi. 309).

For Mars (P. vi. 309), $\pi$ should be increased by $3''.17$; $\theta$ by $68''.35$; $e$ diminished by 0.00000047; $l$ by $19''.27$. The mass of Mars must be diminished by about one-tenth (P. iv. 96).

The total mass of the asteroids is at most not much over one-third of the Earth's mass (C. lii. 1111).

Newcomb's elements of Uranus and Neptune, for mean noon of Dec. 31, 1849, Greenwich time, are as follows (pp. 184, 31, 53, of his Investigation of the Orbit of Uranus, published by the Smithsonian Institution, 1873): —

| Name. | $n$ | $m$ | $a$ | $e$ |
|---|---|---|---|---|
| | $''$ | | | |
| Uranus | 15424.797 | $\frac{1}{21{,}000}$ | 19 1834 | 0.0463592 |
| Neptune | 7864.935 | $\frac{1}{19{,}700}$ | 30.0705 | 0.0084962 |

| Name. | $\pi$ | $\phi$ | $\theta$ | $l$ |
|---|---|---|---|---|
| Uranus | 170° 38′ 48″.7 | 0° 46′ 20″.92 | 73° 14′ 37″.6 | 29° 12′ 43″.73 |
| Neptune | 43 17 30 | 1 47 1.6 | 130 7 33 | 335 5 39 |

Lehmann's elements of the eight principal planets for 1800 (N. 1748) may also be consulted; but it has already been sufficiently shown that, with the exception of the masses, the elements first quoted admit only of small corrections.

790. **Variations of Planetary Elements.** To show the rates at which these elements change, the values of $e$, $\pi$, $\phi$, and $\theta$, 10,000 years before and 10,000 years after 1800 (P. ii.

| Names. | $e$ | $\pi$ | $\phi$ | $\theta$ |
|---|---|---|---|---|
| | | ° ′ | ° ′ ″ | ° ′ |
| Mercury . . . . | 0.2048 | 59 23 | 7 19 50 | 57 21 |
| | 0.2056 | 89 26 | 6 42 50 | 34 29 |
| Venus . . . . . | 0.0129 | 110 1 | 3 6 21 | 99 20 |
| | 0.0035 | 82 47 | 3 2 0 | 47 28 |
| Earth . . . . . | 0.0187 | 78 28 | 1 24 35 | 16 39 |
| | 0.0115 | 134 14 | 1 14 26 | 148 15 |
| Mars . . . . . | 0.0884 | 295 15 | 2 27 51 | 70 29 |
| | 0.1006 | 14 30 | 0 49 17 | 7 49 |

Additions, 29), are given at the foot of the preceding page for Mercury, Venus, the Earth, and Mars. The equinox and ecliptic are those of 1800.

The eccentricities and inclinations of the orbits of the planets are confined within narrow limits. For instance, the eccentricity of the Earth's orbit was 0.0473, and its inclination (to the plane of the ecliptic for 1800) was $3^\circ\ 45'\ 31''$, at a time 100,000 years before 1800. The eccentricity has been diminishing ever since, and will go on diminishing for 23,980 years, amounting then to 0.0033; it will afterwards increase (P. ii. 153). The inclination of the Earth's orbit (P. ii. 163) to the plane of the ecliptic for 1800 can never be as much as 5°.

Another recent investigation of the changes in the planetary elements which require very long periods of time for their completion, and are hence called secular variations, is Stockwell's Memoir on the Secular Variations of the Elements of the Orbits of the eight principal Planets, published at Washington, in 1872, by the Smithsonian Institution. The introduction to this work contains, among others, the following statements. The equinoxes perform a complete revolution in the heavens (by reason of precession) in the average interval of 25,694.8 years; but on account of the secular inequalities in their motion, the time of one of their revolutions may differ from this amount by 281.2 years. The maximum variation of the tropical year is equal to 108.40 seconds of time. The limits of the obliquity of the apparent ecliptic to the equator are $24^\circ\ 35'\ 58''$ and $21^\circ\ 58'\ 36''$; whence it follows that the greatest and least declinations of the Sun at the solstices can never differ at different times more than $2^\circ\ 37'\ 22''$. The eccentricity of the Earth's orbit varies from nothing to 0.0693888.

791. **Examples of the elements of asteroids**, derived from the Berliner Astronomisches Jahrbuch for 1876. The mean distance of Flora is less, and the inclination of the orbit of Pallas to the plane of the ecliptic is greater, than that of any other asteroid yet discovered. The asteroid having

the most eccentric orbit is No. 125 in order of discovery; it has not been named, and its orbit is not known well enough to allow its place to be predicted accurately; but as other asteroids have orbits nearly as eccentric, it will serve as an example. The asteroid having the greatest mean distance is Camilla. Like No. 125, it has escaped the observation of astronomers for some time past, and its orbit cannot be said to be well known; but the mean distances of some other asteroids are not much less than Camilla's. Of the two epochs given for No. 125 and Camilla, the second is that of the mean equinox used in the computation; for Flora and Pallas, the epochs of the equinox and elements are the same.

| Name. | Epochs. | $\mu$ | $a$ | $e$ |
|---|---|---|---|---|
| | | // | | |
| Flora . . | Jan. 1, 1848. | 1086.33038 | 2 2014 | 0.15670 |
| Pallas . . | Nov. 1, 1874. | 768.98579 | 2.7716 | 0.23847 |
| No 125 . | Sept. 12, 1872. | | | |
| | Beginning of 1872 | 670.99 | 3.0352 | 0.34675 |
| Camilla | Dec. 1/4, 1868. | | | |
| | Beginning of 1868 | 528.20 | 3.5602 | 0.12272 |

| Name. | $\pi$ | | | $i$ | | | $\Omega$ | | | $l$ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ° | ′ | ″ | ° | ′ | ″ | ° | ′ | ″ | ° | ′ | ″ |
| Flora . . | 32 | 54 | 28.3 | 5 | 53 | 8.0 | 110 | 17 | 48.6 | 68 | 48 | 31.9 |
| Pallas . . | 121 | 53 | 19.7 | 34 | 41 | 31.0 | 172 | 46 | 53.1 | 67 | 34 | 54 6 |
| No 125 . | 251 | 10 | 25.0 | 6 | 4 | 48.0 | 171 | 9 | 42.0 | 315 | 55 | 54 0 |
| Camilla . | 112 | 49 | 57 6 | 9 | 47 | 41 5 | 175 | 41 | 20.3 | 55 | 57 | 3.6 |

792. **Distances and Synodical Revolutions of Planets.** From the preceding elements may be derived the greatest and least distances of each planet from the Sun and from the Earth, and the period of its synodical revolution. In order that Mercury or Venus should be as near the Earth as possible, it must be at one of its nodes, in aphelion, and at its inferior conjunction, at the moment when the Earth is in perihelion. In order that it should be as far as possible from the Earth, it must be at a node, in aphelion, and at its superior conjunction, at the moment when the Earth is in aphelion. In order that a superior planet should be as near

the Earth as possible, it must be at a node, in perihelion, and in opposition, when the Earth is in aphelion; and in order to be as far as possible from the Earth, it must be at a node, in aphelion, and in conjunction, when the Earth is in aphelion. These combinations of circumstances can seldom or never happen; the distance of a planet from the Earth at any particular conjunction or opposition must be calculated, if it is required, from the places of the planet and of the Earth at the given moment. We will take the Earth's mean distance from the Sun at 92 millions of miles, as above; its greatest distance will then be about $93\frac{1}{2}$, and its least distance about $90\frac{1}{2}$, millions of miles.

The problem of finding the synodical revolution of any planet from that of its sidereal revolution is of the same sort with the question, repeated in most collections of algebraic or of arithmetical examples, "How long after 12 o'clock are the two hands of a clock again together?" Its solution, therefore, may be left to the student; but the approximate synodical periods of the planets, as well as their approximate sidereal periods, are given in the following tables. The years are Julian years of $365\frac{1}{4}$ days each. The distances are stated in millions of miles, but must not be supposed to be known accurately.

| Name. | Sidereal period. | | Greatest distance from Sun. | Least distance from Sun. |
|---|---|---|---|---|
| | Years. | Days. | | |
| Mercury | 0 | 88 | 43 | $28\frac{1}{4}$ |
| Venus | 0 | 225 | 67 | 66 |
| Earth | 1 | 0 | $93\frac{1}{2}$ | $90\frac{1}{2}$ |
| Mars | 1 | 322 | $153\frac{1}{2}$ | 127 |
| Flora | 3 | 97 | $234\frac{1}{2}$ | $170\frac{3}{4}$ |
| Pallas | 4 | 224 | $315\frac{3}{4}$ | $194\frac{1}{4}$ |
| 125 | 5 | 105 | 376 | $182\frac{1}{2}$ |
| Camilla | 6 | 262 | $367\frac{3}{4}$ | $287\frac{1}{4}$ |
| Jupiter | 11 | 315 | $501\frac{1}{2}$ | $455\frac{1}{2}$ |
| Saturn | 29 | 107 | $926\frac{3}{4}$ | $828\frac{1}{4}$ |
| Uranus | 84 | 6 | 1847 | $1682\frac{1}{2}$ |
| Neptune | 164 | 226 | $2787\frac{1}{2}$ | $2739\frac{1}{2}$ |

| Name. | Synodical period | | Greatest distance from Earth. | Least distance from Earth |
|---|---|---|---|---|
| | Years. | Days. | | |
| Mercury | 0 | 116 | 136½ | 47½ |
| Venus | 1 | 219 | 160½ | 23½ |
| Mars | 2 | 49 | 240½ | 33½ |
| Flora | 1 | 161 | 327½ | 77½ |
| Pallas | 1 | 101 | 400½ | 100½ |
| 125 | 1 | 85 | 460½ | 89 |
| Camilla | 1 | 64 | 461½ | 193¾ |
| Jupiter | 1 | 34 | 595½ | 362 |
| Saturn | 1 | 13 | 1020½ | 735 |
| Uranus | 1 | 4 | 1940½ | 1589 |
| Neptune | 1 | 2 | 2881 | 2645¾ |

Greatest distance of Venus, at inferior conjunction, from the Earth . . . . 27½ million miles.
Greatest distance of Mars, at opposition, from the Earth . . . . . 62¾ ,, ,,

Hence Mars may be nearly twice as far from the Earth at one opposition as at another.

793. **Bulk and Density of Planets.** The bulk of a planet may be readily calculated when we know its distance and apparent diameter; and its density may then be found from its bulk and mass. But as we have seen, the masses of the planets are not precisely determined; their distances depend on the Sun's parallax, our knowledge of which is still unsatisfactory; and their apparent diameters must be obtained from measures of their disks, which are difficult to execute with precision, as will appear by the following figures, collected by Kaiser (L. 213 to 274). The apparent diameter of Mercury, at a distance equal to the semiaxis major of the Earth's orbit, ranges, according to different observers, from 5″.2 to 6″.9; that of Venus from 16″.6 to 17″.9; the apparent equatorial diameter of Mars from 9″.6 to 9″.2; its apparent polar diameter from 9″.4 to 9″.2. Similar disagreements appear in different estimates of the apparent diameters of Jupiter, Saturn, Uranus, and Neptune, at a distance for each planet equal to the semiaxis major of its orbit. Thus the equatorial diameter of Jupiter ranges from 39″.5 to 37″.1; its

polar diameter from 37″.9 to 35″.1; the equatorial diameter of Saturn from 18″.5 to 16″.9; its polar diameter from 16″.8 to 15″.1; the diameter of Uranus from 2″.9 to 3″.6; that of Neptune from 2″.5 to 4″.4. The polar compression of Jupiter, according to different observers, ranges from $\frac{1}{14}$ to $\frac{1}{20}$; that of Saturn from $\frac{1}{9}$ to $\frac{1}{15}$; those of other planets cannot as yet be said to be even approximately known; and different measurements of Saturn's ring differ enough to make exact statistical statements of its dimensions somewhat illusory. The following table will give some notion of the bulk and density of the planets as compared with the Sun and with the Earth. It has been formed from approximate apparent diameters derived from the figures just quoted, the Earth's apparent diameter at its mean distance from the Sun being 17″.8, or twice the solar parallax 8″.9. The masses of the planets have been corrected by the data already given.

| Name. | Apparent diameter. | | Ratio of diameter to Earth's. | Ratio of mass to Earth's. | Ratio of density to Earth's. |
|---|---|---|---|---|---|
| | At mean distance from Sun. | At Earth's mean distance from Sun. | | | |
| | ″ | ′ ″ | | | |
| Sun. . . . . | . . . | 32 3 | 108.03 | 320,000 | 0.25 |
| Mercury . . . . . | 15.5 | 0 6 | 0.34 | 0.06 | 1 53 |
| Venus . . . . . | 23.5 | 0 17 | 0.96 | 0.78 | 0.88 |
| Mars . . . . . | 6.1 | 0 9.3 | 0.52 | 0.11 | 0.78 |
| Jupiter . . . . . | 37.4 | 3 14.6 | 10.93 | 305 | 0.23 |
| Saturn . . . . . | 16.8 | 2 40 3 | 9.01 | 91 | 0.12 |
| Uranus . . . . . | 3.3 | 1 3.3 | 3.56 | 15 | 0 33 |
| Neptune . . . . . | 3.4 | 1 42.1 | 5.74 | 16 | 0.08 |

The student only needs a knowledge of arithmetic, and of the facts contained in this book, to enable him to construct similar tables for other values of the apparent diameters of the planets; since these angles are so small that their arcs may be used for their tangents. The ratio of the bulk of one globe to that of another may be expressed by the ratio of the cubes of the diameters of the globes. It will be found that the relative densities of the planets will vary considerably according to the diameters which may be used in the calculation.

794. **Rotation of Planets.** The time of rotation of Mars, according to Kaiser, who regards it however as not yet determined to the tenth of a second (L. 80), is $24^h\ 37^m\ 22^s.6$ mean time (L. 76, 77). According to Schmidt (N. 1965), it is $24^h\ 37^m\ 22^s.603$. Proctor's value is $24^h\ 37^m\ 22^s.735$ (Essays on Astronomy, Appendix A). The period of Jupiter's rotation, according to various observers, ranges from $9^h\ 50^m$ to $9^h\ 56^m$ (N. 1973); it varies to some extent according to the part of the disk which is observed; see Lohse's paper in Vol. II. of the Bothkamp Observations, Leipzig, 1873. W. Herschel found that Saturn's rotation occupied $10^h\ 16^m$ (H. 1794) His value for the inclination of the axis of Mars to the plane of that planet's orbit is 61° 18′, according to which the obliquity of the ecliptic of Mars is 28° 42′ (H. 1784). The exact determination of the poles of Jupiter and Saturn has not been found practicable.

795. **Satellites.** The following numbers relating to the satellites (except the Moon's apparent diameter) have been derived from the tables in J. J. von Littrow's "Wunder des Himmels," fifth edition, revised by Karl von Littrow, and published at Stuttgart in 1866. This work gives the original authorities for its statistics.

| | |
|---|---|
| Sidereal revolution of the Moon, in mean time | $27^d\ 7^h\ 43^m\ 11^s.5$ |
| Synodical revolution of the Moon, in mean time | 29 12 44 2.9 |
| Eccentricity of the Moon's orbit | 0.05490807 |
| Inclination of the Moon's orbit | 5° 8′ 39″.96 |
| Inclination of Moon's equator to the ecliptic | 1° 28′ 25″ |
| Tropical revolution (revolution with respect to the vernal equinox) of the Moon's perigee | 8.8473 Julian years |
| Tropical revolution of the Moon's nodes (period of Earth's lunar nutation and tropical period of Moon's precessional movement) | 18.6128 „ „ |

| | |
|---|---|
| Mean equatorial horizontal parallax of Moon . . | 57′ 2″.06 |
| Mean distance of Moon, in equatorial diameters of the Earth . . . . . | 30.1389 |
| Ratio of mass of Moon to Earth's mass . . . . | $\frac{1}{80}$ |
| Ratio of apparent semidiameter of Moon to its equatorial horizontal parallax (by Peirce's tables of the Moon) . . . . . | 0.272274 |

Unless we wish to be very accurate, we may take the last ratio for that between the Moon's actual diameter and the Earth's.

The following table, under the heading "Distance," contains the ratio of the mean distance of each satellite from its primary to that of the Earth from the Sun; under the heading "Inclination," the angle between the plane of the satellite's orbit about its planet, and that of the ecliptic, except for Jupiter's satellites; the inclinations of their orbits here given are inclinations to the plane of Jupiter's orbit. The column headed "Period" contains the period of the sidereal revolution of each satellite about its planet, stated in days of mean time. The apparent diameters of Jupiter's satellites are respectively 1″.015, 0″.911, 1″.488, 1″.273, at the Earth's mean distance from Jupiter; these measurements are liable, of course, to considerable inaccuracy.

| Name. | | Distance. | Inclination. | Period. |
|---|---|---|---|---|
| Satellites of Jupiter | I. | 0.002819 | 3° 5′ 24″ | 1.769 |
| | II. | 0.004483 | 3 4 25 | 3.551 |
| | III. | 0.007155 | 3 0 28 | 7.155 |
| | IV. | 0.012585 | 2 40 58 | 16.689 |
| Satellites of Saturn | Mimas | 0.00124 | Uncertain. | 0.942 |
| | Enceladus | 0.00159 | Uncertain. | 1.370 |
| | Thetis | 0.00197 | 28° 10′ | 1.888 |
| | Dione | 0.00254 | 28 10 | 2.737 |
| | Rhea | 0.00352 | 28 8 | 4.517 |
| | Titan | 0.00817 | 27° 33′ 47″ | 15.945 |
| | Hyperion | 0.00989 | Uncertain. | 21.284 |
| | Iapetus | 0.02380 | 18° 38′ | 79.329 |
| Satellites of Uranus | Ariel | 0.00138 | Uncertain. | 2.520 |
| | Umbriel | 0.00192 | Uncertain. | 4.145 |
| | Titania | 0.00315 | 100° 34′ | 8.706 |
| | Oberon | 0.00420 | 100 34 | 13.463 |
| Satellite of Neptune | | 0.00237 | 150° | 5.878 |

The satellites of Uranus have retrograde movement around it; hence their inclinations are set down at 100° 34′ instead of 79° 26′. The satellite of Neptune also probably retrogrades, and its inclination is therefore 150° instead of 30°.

796. **Incandescence.** According to Draper (J. 1847, iv. 388) the shining of an object at a less heat than 977 degrees Fahrenheit is to be considered phosphorescence rather than incandescence. When a solid or liquid body is gradually heated, the first light which it emits on becoming incandescent is red, and the body is said to be red hot. The light of phosphorescence is usually bluish or greenish.

797. **Ether and Atmosphere.** It is generally thought that no space is absolutely empty. Some philosophers hold that gases like those which constitute the Earth's atmosphere exist in a highly rarefied condition throughout the universe (Z. 92). In this case, these gases may perhaps be regarded as constituting the medium which transmits to us the light of celestial objects and is called the ether (C. xxxix. 529). Zöllner considers it probable that the absence of any perceptible atmosphere about the Moon is due to the smallness of its mass, and that the small mass of Mercury favors the supposition that it has no atmosphere. On these principles the atmosphere of Mars cannot be chiefly composed of gases like the oxygen and nitrogen of our atmosphere (Z. pp. 102 to 105).

798. **Numbering of Comets.** Chambers, in the list of comets in his Descriptive Astronomy, arranges them by their perihelion passages; but Donati's Comet (for instance) is usually called the fifth of 1858 rather than the sixth, as it would be by order of perihelion passages.

799. **Example of the Elements of a Comet** (N. 2003).

Mean Berlin time of perihelion passage, 1874, July 8.89385.

Longitude of perihelion 271° 6′ 19″.5
Longitude of ascending node 118° 44′ 25″.3 . . . . . } mean equinox, 1874.0
Inclination of orbit to ecliptic 66° 20′ 58″.6 . . . . . }

Eccentricity, 0.99872. Semiaxis major, 529.51.
Period of revolution, 12,184.3 years.

This comet was the third of 1874, usually called Coggia's Comet, from its discoverer. If the elements just given are correct, the comet will return when Vega is the North Star (168).

800. **Tropical and Anomalistic Years.** The yearly amount of precession being $50\frac{1}{4}''$ (785), the tropical year is less than the sidereal year by the time in which the mean motion of the Earth in longitude amounts to $50\frac{1}{4}''$. In other words, the tropical year is to the sidereal year (788) as $1{,}295.949\frac{3}{4}$ is to 1,296,000, the number of seconds in 360°. The tropical year is therefore about 365.2422 days of mean time.

The yearly advance of the apsides of the Earth's orbit is about 11″.8 (O. 243); the anomalistic year is therefore about 365.2597 days of mean time.

801. **Illumination of Dark Side of Venus.** Gruithuisen's fanciful hypothesis on this subject (343) may be found in his "Astronomisches Jahrbuch . . . . für das Jahr 1842," p. 159, note.

802. **Height of Shooting Stars and of Auroras.** On these subjects, see J. 1868, xlv. 235; N. 1581, 1662; J. 1865, xxxix. 286; 1871, i. 128; 1872, iii. 273.

803. **Variability of the Earth's Rotation.** See Thomson and Tait's Treatise on Natural Philosophy, Vol. I. p. 686, on the retardation of the Earth's rotation by tidal action; and Newcomb on the variability of the rotation (J. 1874, viii. 161).

804. **Optical Theories.** Van der Willigen has lately written a paper on the untenability of the opinion that the movement of a luminous body or of the prism through which it is observed can affect the refrangibility of its light. The paper has been published in French. The Dutch version is in the Verslagen en Mededeelingen der K. Akademie van Wetenschappen, Afdeeling Natuurkunde (for 1873).

Recent experiments by Draper (J. 1872, iv. 161; 1873. v. 25, 91) have apparently disproved the formerly prevalent theory of three spectra (495).

805. **Mean and Sidereal Time.** If we know the places, at a given moment, of the hands of a clock set to either of these kinds of time, we can find the corresponding places of the hands of a clock set to the other kind of time, by means of the data given in all large almanacs. These data include the mean times of the upper culminations of the vernal equinox, or the sidereal times of mean noon, for some given meridian; and as these times change from year to year, they cannot be given except for some particular year. Hence, in order to find them, the almanac must be consulted.

806. **Form of Orbits under the Laws of Gravitation and Inertia.** The following statements are from Price's Treatise on Infinitesimal Calculus, Vol. III. (Oxford, 1856), pages 478, 480, 485. Suppose a particle to be projected with a given velocity from a given point and in a given line: and to move under the action of an attractive force which is always directed towards a second given point, and varies inversely as the square of the distance between the point to which it is directed and the moving particle. According as the velocity with which the particle was projected is less than, equal to, or greater than, that which would be acquired by the particle moving from an infinite distance, under the action of the attractive force, to the point from which it was projected, so will its orbit be an ellipse, a parabola, or a hyperbola, with the centre of force in the focus. In this statement, the circle is regarded as one kind of ellipse. If the particle is projected from an apse with a velocity such that the centrifugal force is equal to the attractive force, the orbit of the particle is a circle.

807. **Times of High and Low Tide.** There is a geometrical demonstration by Airy (Mn. xxvi. 228) that the consequence of the constant change of place of any part of the Earth with respect to the Moon (if we suppose the ocean to occupy the equatorial parts of the Earth's surface and the water to move without friction), would be to make it always low water under the Moon, so that each high tide would

come a quarter of a lunar day after one of the Moon's culminations. In fact, as we have already seen (674), there is often a still longer interval between the times of the Moon's culmination and of high tide.

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